A weather-type hydrologic approach to runoff phenomena

van de Griend, A.A.

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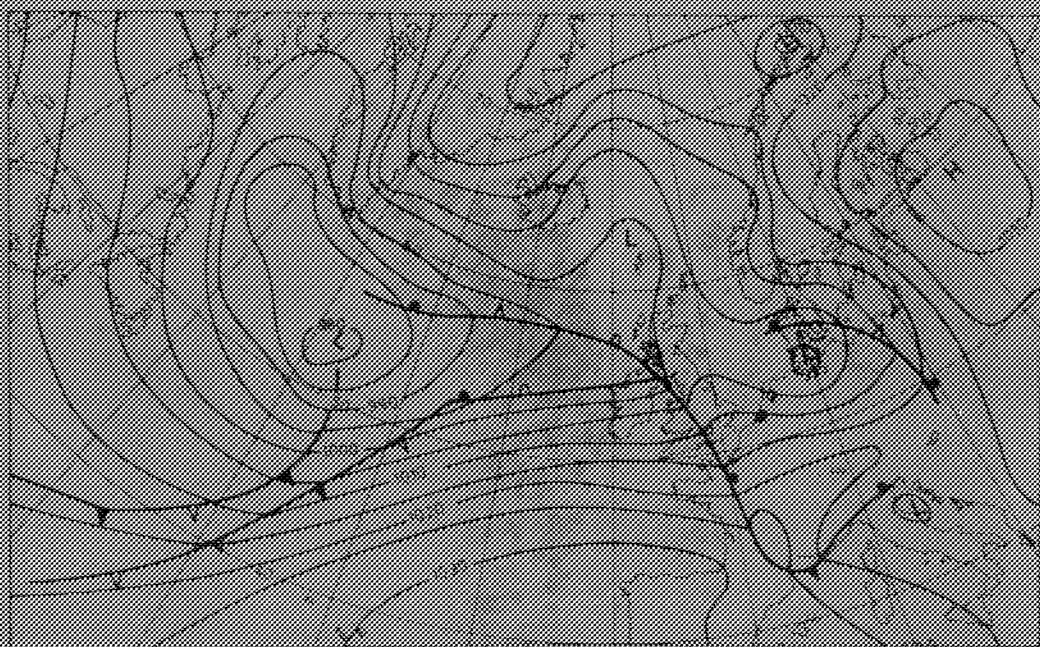
TO
RUNOFF PHENOMENA



A. A. VAN DE GRIEND

VRIJE UNIVERSITEIT TE AMSTERDAM

A WEATHER-TYPE HYDROLOGIC APPROACH TO RUNOFF PHENOMENA

A case-study applied to the Alpine
catchment of the river Ahr
Southern-Tyrol, Italy

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van
doctor in de wiskunde en natuurwetenschappen
aan de Vrije Universiteit te Amsterdam,
op gezag van de rector magnificus
dr. H. Verheul,
hoogleraar in de faculteit der wiskunde en natuurwetenschappen,
in het openbaar te verdedigen
op woensdag 15 april 1981 om 13.30 uur,
in het hoofdgebouw der universiteit,
De Boelelaan 1105

door

ADRIAAN ANTON VAN DE GRIEND

geboren te Oud-Beijerland

Rodopi

AMSTERDAM 1981

Promotor : Prof. dr. G.B. Engelen
Coreferenten : Prof. dr. F. Fliri
Prof. dr. I. Simmers

STELLINGEN

1. De in de hydrologische handboeken* beschreven methoden voor het bepalen van leegloopkarakteristieken langs grafische weg uit afvoerverloopkrommen behorend tot het niveo-glaciale regime, berusten op een foutief inzicht in het voedingsproces.

   *Garstka, W.U. (1964) — In: Ven Te Chow (Ed.), Handbook of Applied Hydrology, McGraw-Hill, Section 10, Snow and Snow Survey, pp. 10-35/10-38.

   *Martinec, J. (1976) — In: Rodda, J.C. (Ed.), Facets of Hydrology, John Wiley & Sons, Chapter 4, Snow and Ice, pp. 99-106.

Aangezien de GROSSWETTERLAGEN volgens Franz Bauer betrekking hebben op een grote ruimtelijke uitgestrektheid, aangeduid door de lettergreep "GROSS", doch tevens de karakteristieke ontwikkeling van het weer in zich dragen, in de duitse taal aangeduid als "WITTERUNG", is het beter te spreken van GROSSWITTERUNGSLAGEN dan van GROSSWETTERLAGEN.

(Dit proefschrift)

3. Patroonherkenning vormt een wezenlijk onderdeel van de geografische hydrologie en kan als zodanig een belangrijke bijdrage leveren tot het inzicht in de samenhang en de ruimtelijke spreiding van aan het vóórkomen van water gerelateerde verschijnselen.

4. Van de in de literatuur beschreven denkbeelden over het stroomgebied als dynamisch afvoergenererend systeem — neergelegd in het *"dynamic source-area concept"* — moet een belangrijke bijdrage worden verwacht tot verbetering van de conventionele op het *"looptijd- en bergingsbeginsel"* gebaseerde modellen voor praktische afvoervoorspelling.

5. Het in stelling vier genoemde *"dynamic source-area concept"* kan worden beschouwd als een variant van het in 1961 door Ernst* beschreven concept van aan het drainagesysteem en aan fluctuerende grondwaterstanden gekoppelde variabele deelsystemen, die bijdragen tot de afvoer.

   *Ernst, L.F. (1961) — Grondwaterstromingen in de verzadigde zone en hun berekening bij aanwezigheid van horizontale evenwijdige open leidingen. Proefschrift, Rijksuniversiteit te Utrecht, Pudoc — Wageningen (Fig. 21, blz. 46).

6. Omdat de bestaande weertypen-klassifikatiesystemen ontwikkeld zijn als basis voor het bestuderen van de dynamische klimatologie, verdient het aanbeveling, daarnaast een op de samenhang tussen *weertypen* en *hydrologie* gerichte weertypen-klassifikatie te ontwikkelen.

7. Vanwege de steile gradienten van de hangende glaciale dalen in het alpine hooggebergte en de daarmee samenhangende hoofdzakelijk eroderende werking van gletsjers gedurende het Pleistoceen, zijn grondmorenes in deze dalen eerder uitzondering dan regel.

8. Het gebruik in Indonesië van uit Europa en de V.S. afkomstige, doch dáár verboden pesticiden en insecticiden, zoals b.v. endrine, is verwerpelijk, ondermeer in verband met het optreden van massale vissterfte in sawagebieden en in viskweekvijvers die met de drainagesystemen van de sawa's in verbinding staan.

9. Daar de hydrologie zich heeft ontwikkeld tot een zelfstandige wetenschappelijke discipline zou invoering van een doctoraalexamen *hydrologie* in het akademisch statuut meer recht doen aan de huidige situatie.

10. Gelet op stelling negen en de grote maatschappelijke betekenis van met water verbonden problemen is het wenselijk dat de gezamenlijke hogescholen en universiteiten waar hydrologie gedoceerd wordt, bij de minister van onderwijs een verzoek doen tot instelling van een landelijke postdoctorale beroepsopleiding hydrologie.

11. Aangezien het roken tijdens vergaderingen en in openbare gebouwen onuitroeibaar blijkt, verdient het aanbeveling, gezien de sterke filtrerende werking van de longen, de rokers te verzoeken ononderbroken te inhaleren, om de schadelijke gevolgen voor de passieve roker zo veel mogelijk te beperken.

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Sudden, the ditches swell; the meadows swim.
Red, from the hills, innumerable streams
Tumultuous roar, and high above its banks
The river lift; before whose rushing tide,
Herds, flocks, and harvests, cottages and swains,
Ro'll mingled down; all that the wind has spar'd
In one wild moment ruin'd
the big hopes
And well-earn'd treasures of the painful year.

From: The Seasons, James Thomson

To my parents
To Rita and Nicole

P R E F A C E

I wish to express my sincere gratitude to the following persons who supported me with their aid and encouragement during the realisation of this thesis:

Prof. Dr. G.B. Engelen, for the confidence he had in me, and for the many profound and fruitful discussions which contributed much to the results of this investigation.

Prof. Dr. F. Fliri, for the discussions I had with him at his institute in Innsbruck during the initial phase of the investigation, for reading the manuscript and for his valuable suggestions.

Prof. Dr. I. Simmers, for his critical reading of the manuscript and the useful remarks.

Prof. Dr. M. Schüepp, for inviting me to his institute in Zurich, for our correspondence concerning the various aspects of weather-type classification and for the numerical descriptions of weather-situations he placed at my disposal.

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Drs. M. Kersten, for the many hours he spent on the implementation of the data-base, used for processing the numerous hydrologic and meteorologic data.

Drs. A. de Goffau, for the programming he did.

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Last but not least I am highly grateful to my wife Rita, for her continuous moral support and for typing the manuscript, and to our daughter Nicole for entering the world in the last stage of this investigation, thus sharing the finishing touch of my work.

C O N T E N T S

I N T R O D U C T I O N

Purpose and Scope

Medium range forecast of river runoff is of importance for effective hydrologic management of discharge areas and rivers with respect to flood control, reservoir regulation, etc.

For purposes of medium range runoff forecasting, use is made nowadays of models, which, depending on application and the areal extent of the catchment, may roughly be subdivided into:

a) those which describe the transformation of input to output by the catchment, where the input is derived from estimated meteorological parameters (precipitation, temperature, radiation, etc.) and the output consists of river runoff,

b) those describing the transformation of an observed runoff hydrograph between a location some distance upstream and the downstream point of prediction. This latter method, which is known as flood routing, is mainly applied in large river systems.

It is a well known fact that, in general, the description of the system operation (using a black-box, a grey-box or a white-box approach), in order to simulate the transformation as expressed under a), offers relatively few problems, both for catchments with runoff from precipitation (W.M.O., 1967, 1975a, 1975b; Overton and Meadows, 1976) as well as for catchments with mainly runoff from snowmelt (Martinec, 1960, 1965, 1970, 1976; Herrmann,1974; W.M.O., 1979), the latter being more problematical when the combined effect of rainfall and snowmelt is concerned (Hoeck, 1952; U.S.A. Corps of Eng., 1956; Popov, 1972). Therefore, the inaccuracy of medium range runoff forecasting should not be ascribed primarily to the models used, but rather to inaccurate medium range prediction of rainfall and temperature.

During the last few decades great progress has been achieved by meteorologists in predicting the air circulation several days in advance, using multilayer numerical models (see for ex. Kletter, 1957; Manabe et al., 1965; Arpe et al., 1976). The prediction of 1000 mb and 500 mb charts ten days in advance for Western Europe is performed routinely by the "European Centre for Medium Range Weather Forecast (ECMWF)", in Reading, England, since 1979.

As a result of differences in position with respect to the general circulation and, particularly in the Alpine region as a result of differences in altitude, relief and orography, the weather during one specific circulation type may vary widely from one location to another (Schüepp, 1959a; Fliri, 1962b; Steinhauser, 1962; Kirchhofer, 1971). Still, the circulation should be regarded as the driving force of the hydrological processes, in the sense that the circulation governs the input in terms of rainfall, temperature, radiation and other meteorological parameters. Therefore, it is expected that runoff phenomena of a particular catchment are closely related to the types of circulation, especially on the medium term, and that knowledge of these relations in turn can be used to translate information on future circulation into future runoff phenomena.

Until now little is known about the relations between the occurrence of circulation types and hydrologic phenomena of discharge areas and therefore this area of investigation can be regarded as an unexplored field in hydrology. Only a few scientists have worked in this field. Wehry (1966) investigated the relations between the occurrence of GROSSWETTERLAGEN, according to the classification of Baur-Hess/Brezowsky, and rainfall totals exceeding 50 mm, with respect to the occurrence of floods. Tröschl (1967) analysed the rainfall and flood catastrophes in November 1966 in the southern Alps. Schwarzl occupied himself in particular with the Vb-situations according to Van Bebber, as characteristic flood-creating circulation types in the eastern Alps (Schwarzl, 1965, 1971, 1972) and De Bruin and Schuurmans (1978) described the meteorological situations which led to extremely low water levels of the river Rhine in 1959 and 1964, as a contribution to the "Monography on the River Rhine". De Bruin et al. (1978) described the meteorological situation which led to extremely high water levels in the river Rhine in February and March 1970. Application of statistical relationships between the general character of the atmospheric circulation during the winter season and long-range hydrologic phenomena with special reference to ice breakup in large rivers during spring has been reported from Russian experience by Apollov et al. (1970).

Only by systematic investigations a better insight can be achieved into the relations between circulation types and hydrologic phenomena, thus starting to fill the unexplored field of WEATHER-TYPE HYDROLOGY. A weather-type hydrologic approach, as a new development in hydrology, with its own contribution to hydrologic forecasting, should be based on both synoptic meteorology on the one hand and surface water hydrology on the other, and requires as such a strong integration between both disciplines.

The current investigation concerns hydrologic phenomena of the Alpine nivo-glacial catchment of the river Ahr in Southern-Tyrol (Italy) in relation to types of circulation and enters into the problem of runoff forecasting on the basis of forecast weather charts. The river Ahr catchment covers an area of 148 km^2 upstream of the gauging station used for the investigation.

Although its application may be very useful for large river systems, it is found that insight into the fundamental relations between weather-types and hydrologic behaviour can best be achieved by investigating a small catchment.

Inasmuch as the study area, mainly through its position with respect to the Alpine central divide and the general circulation of the atmosphere, takes a central place in the investigation and in the procedures followed, a general picture will first be presented of its location, geography, geology, climatology and hydrology in chapter I.

In order to investigate hydrologic phenomena in relation to weather-types one is committed to an objective classification of such types. Chapter II treats the subject of weather-type classification. Hydrologically relevant classes of weather-types will be defined on the basis of observed meteorological parameters and considerations on air-mass advection, which form the basis for the analysis of weather-type hydrologic phenomena described in chapter III.

Chapter IV deals with a weather-type runoff forecasting model which is tested for the prediction of 10-day mean, 10-day highest and 10-day lowest daily runoff in correspondence with the current 10-day medium-range forecast of weather charts by the above mentioned ECMWF.

Statistical and Mathematical Methods

For the sake of readability, especially for the less mathematically orientated reader, detailed information on statistical methods and mathematical theory is presented in an appendix.

Data Processing

Hydrological and meteorological data from the 23-year period 1953-1975 were used for the investigation. Data on runoff, precipitation, temperature and snow cover were only available in annual reports and partly on observer sheets and had to be converted into computer readable form. Most of these data were retrieved from annual reports (Annali Idrologici) of the "Ufficio Idrografico Del Magistrato alle Acque Venezia".

Numerical descriptions of daily weather situations in the Alpine region during the period 1953-1975 were placed at my disposal in computer readable form by the "Schweizerische Meteorologische Zentralanstalt", Zurich.

Two computer systems were used for the data processing. One of these computers is the PDP-11/45 in the Subfaculty of Mathematics, Free University, Amsterdam. The other is the CDC-6600/Cyber of the Stichting Academisch Rekencentrum, Amsterdam. The two systems are interconnected by means of a data-link.

In order to perform complex retrievals from the data, a data-base was created on the PDP-11/45 (Van de Griend & Kersten, 1977), which makes use of the relational DBMS Ingres, developed at the University of California by Stonebraker et al. (1976). The CDC-6600/Cyber was used for actual computations.

Fortran programs for correlation, regression and factor analysis were at my disposal for use on the CDC-6600/Cyber. Special programs for analysis of variance, multinomial analysis, time-series analysis and hydrograph analysis were compiled by the author for use on the PDP-11/45 and the CDC-6600/Cyber.

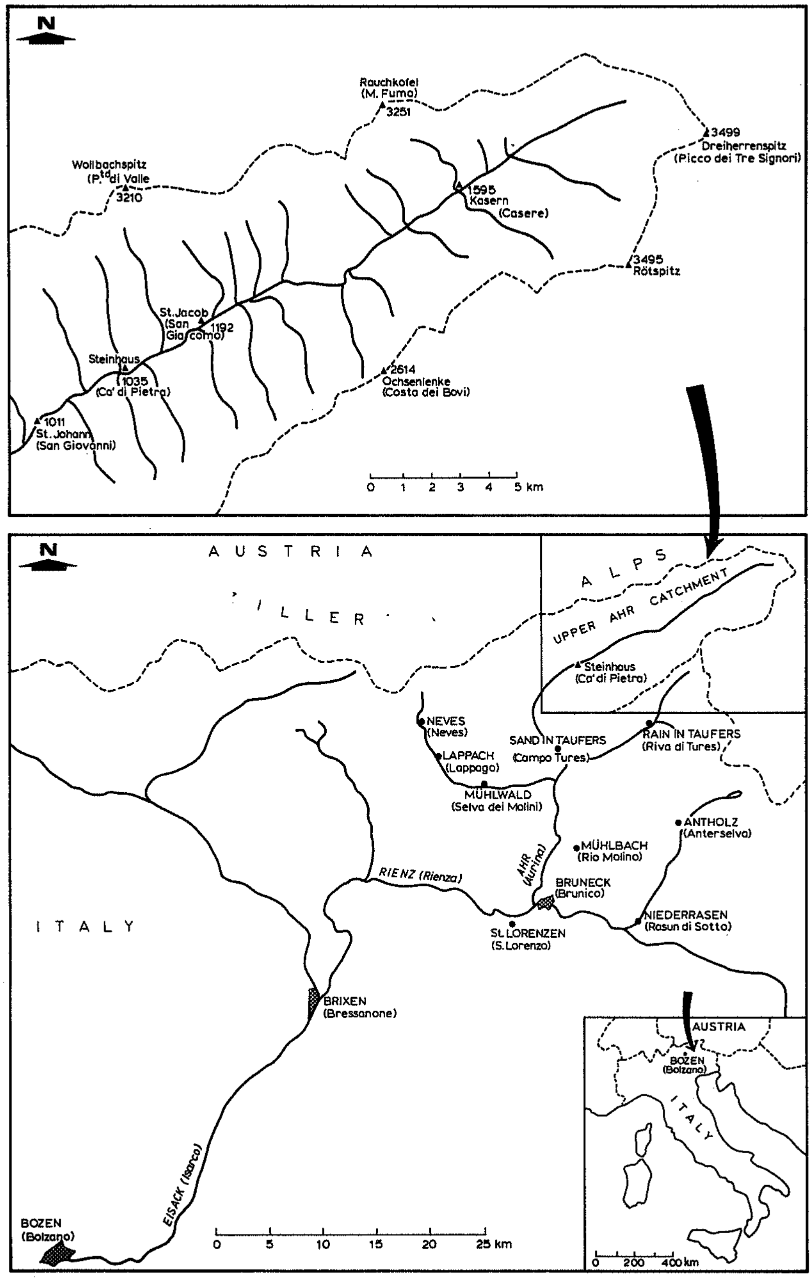


Fig. 1.1 Location Map of the Study Area (The River Ahr Catchment)

CHAPTER I

STUDY AREA

(The River Ahr Catchment)

. GEOGRAPHY

1.1 Location

The river Ahr *(Aurino)** is situated on the southern side of the main ridge of the Zillertal Alps in Southern Tyrol, Northern Italy. The river Ahr rises from the Dreiherrenspitze(3499 m)/*(Picco dei Tre Signori)* as a glacial river and drains an area of about 600 km^2 into the river Rienz *(Rienza)* near Bruneck *(Brunico)*, see fig. 1.1.

The investigation under consideration is related to the upper-Ahr catchment from which runoff has been measured since 1926 at the gauging station Steinhaus (1035 m)/*(Ca'di Pietra)*. The upper-Ahr catchment has an area of 148 km^2.

1.2 Topography

The upper-Ahr flows in a typical U-shaped glacial valley with hanging tributary valleys and truncated spurs. The valley is bordered to the north by the Zillertal Alps. The elevations of the northern water divide vary around 3000 m. The southern water divide extends from the Dreiherrenspitze(3499 m) to the south-west. The elevations of the peaks on the southern divide gradually decrease to the west towards the Ochsenlenke (2614 m)/*(Costa dei Bovi)*.

The upper-Ahr valley is characterized by a sequence of erosion levels at different elevations, intersected by steep glacial valleys. This structure is partly derived from fluvial origin by phases of extensive vertical uplift and vertical erosion, alternating with periods of higher vertical stability and mainly lateral erosion, a process which should have started in Miocene times and continued during the Pleistocene (Hannβ, 1967). During the Pleistocene, glacial activity must have accentuated the transitions between the erosion levels, thus forming steep valleys and head walls.

* *In view of the fact that German is the principal language in this, since 1919 Italian territory (see e.g. Gruber, 1975), only the German topographic names will be used in cases of recurrence. A list of German and corresponding Italian names is presented in Appendix C.*

1.3

The elevation-area distribution is best characterized by the hypsometric curve (fig. 1.2), in which three zones can be distinguished which are all of direct importance for the hydrologic regime. These are:

a) The steep glacial U-shaped valley, ranging from 1000 m to about 1700 m.

b) The transition zone, consisting of Tertiary and early Pleistocene erosion levels, ranging from about 1700 m to about 2700 m.

c) The steep crests and peaks forming the water divides and bordering the highest Tertiary levels, rangeing from about 2700 m to about 3500 m.

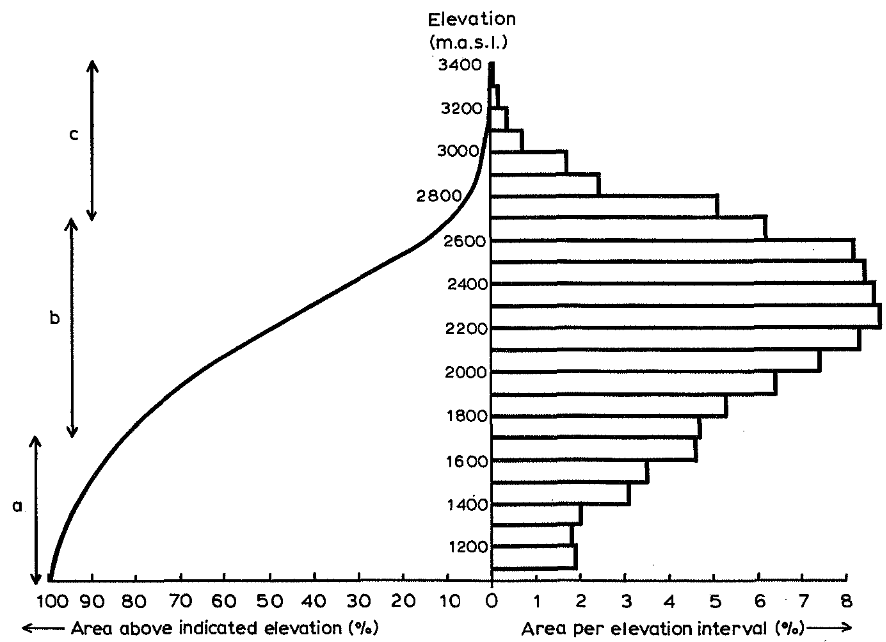


Fig. 1.2 Hypsometric curve of the upper-Ahr catchment (total area 148 km^2)

a) U-shaped glacial valley
b) Tertiary and early-Pleistocene erosion levels
c) Steep crests and peaks

1.3 Vegetation and Land-use

The areal distribution of vegetation is governed by topography, geomorphology and altitude and has to a high degree been influenced by human activity (Schiechtl & Stern, 1976). The vegetation has been subdivided by Schiechtl and Stern into three zones: the Alpine zone, the sub-Alpine zone and the mountainous zone.

The main valley bottom, the alluvial fans, and the adjacent lower valley walls consisting of colluvium, are used as hay-fields and for vegetable growing. The steeper parts of the main valley walls, the actual trough-walls, belong to the mountainous zone and are covered with spruce-fir and to a smaller degree with larch. The higher erosion levels and terraces - above 1600 m - are in use as Alpine meadows. The steeper parts in this zone are also covered with spruce-fir and larch and belong to the sub-Alpine zone. Above 2000 m, in the Alpine zone, vegetation is sparse and consists mainly of Alpine grasses and shrubs (vegetation map of Tyrol by Schiechtl & Stern, 1976; see also Rutz, 1968).

2 GEOLOGY

The river Ahr incised its course near the border of the Tauern Window, where the Penninic nappe outcrops from under the Austro-alpine nappe and plunges south under the latter (fig. 1.3, a and b). The Penninic nappe to the north of the river Ahr consists of granodioritic orthogneis. It results from acidic rocks which intruded into the Penninic zone during late-Hercynian time (Angenheister et al., 1972), and has been metamorphosed into the so-called "Zentralgneis" during the Alpine orogeny, due to "Tauern Kristallisation", which started at the Cretaceous-Tertiary boundary (Karl, 1959). To the south of the river Ahr extend the slate covers ("Schieferhüllen") of the "Zentralgneis", which have been subdivided into an upper ("Obere") and a lower ("Untere") slate cover ("Schieferhülle"). The "Untere Schieferhülle", which is partly autochtonous or para-autochtonous relative to the "Zentralgneis" (Angenheister et al., 1972), comprises various rock types, varying from Paleozoic paragneis to metamorphic limestone, serpentine and prasinite of Permo-Triassic age (Dal Piaz, 1929). The "Obere Schieferhülle" is a real nappe, and consists of a slate complex: the "Bundner Schiefer" with ophiolites and some Permo-Triassic rocks. The actual transition to the overlying Austro-alpine nappe to the south is formed by the "Matreier Zone", which

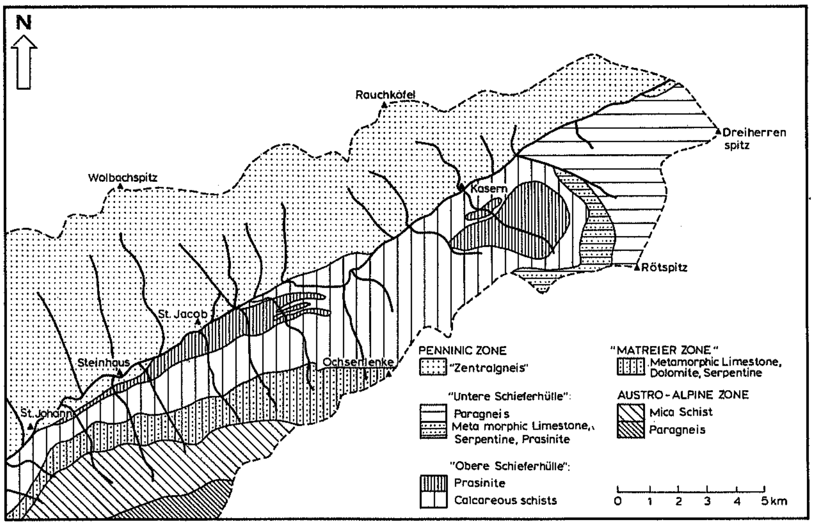
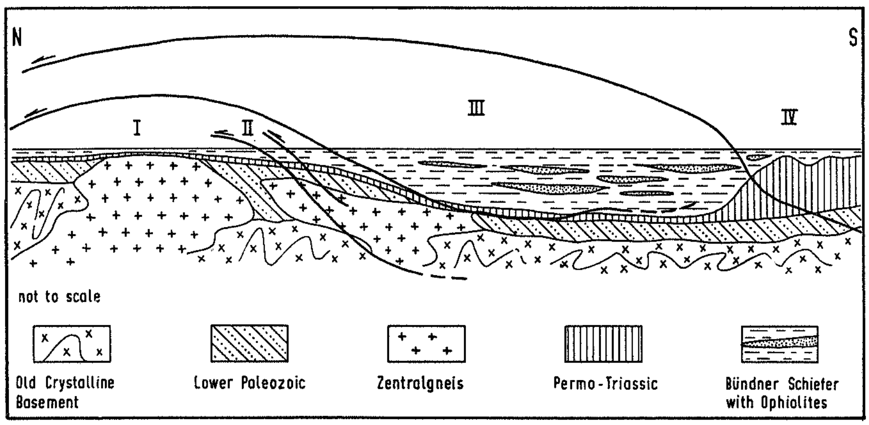


Fig. 1.3[a] Geological map of the upper-Ahr catchment (Simplified from Hannß, 1967)



The diagram shows the situation at about Lower Cretaceous.
I (Par)autochthonous massifs and "Schieferhüllen" (slate covers)
II Imbricate structures and recumbent folds of the "Untere Schieferhülle"
III Nappes of the "Obere Schieferhülle"
IV Austroalpine Nappes

Fig. 1.3[b] Cross section through the Penninic Zone of the Tauern Window according to Frasl & Frank (1966) (From Angenheister et al., 1972) consists of a sequence of metamorphic limestones, dolomites and serpentines. The Austro-alpine nappe consists of old metamorphic rocks of the so-called "Altkristallin", such as mica-schists and paragneis of Paleozoic age. They are considered to be the crystalline basement of the upper Austro-alpine units (Troll et al., 1976). A very extensive study and description of the geology of the Alps, including this region, has been made by Tollmann (1963, 1977). An ouline map of Tyrol has recently been compiled by Brandner (1981).

3 CLIMATE

3.1 General

Most of the existing methods for the description of climate (see for ex. Blütghen, 1966) are based on mean values of meteorological parameters and give no information on frequency and variability *(coefficient of variation)* of meteorological parameters. In general, therefore these methods are of little practicle value. This is indeed the case for Alpine areas, where differences of the weather and variability of meteorologic elements are largely determined by position with respect to orography and elevation (Fliri, 1975). In modern climatology, more emphasis is laid on the dynamic character of the weather. Built on the work by Flohn (1954), Fliri worked towards a dynamic climatological description of the Alpine area of Tyrol (Fliri, 1962a, 1974). In a very extensive work, Fliri proposed a new climatic typification for Tyrol, based on (a) elevation-related belts with respect to maximum temperature in July, (b) annual precipitation, (c) the variability of annual precipitation and (d) the distribution of precipitation during the year (Fliri, 1975).

According to this classification, the climate of the upper-Ahr valley can be described as a typical high-mountain climate, with a characteristic vertical gradient of temperature and precipitation, distinguished in three elevation belts, a strongly marked precipitation maximum in summer and a small variability of the annual precipitation (< 18%).

More attention is given in this study to the climatic elements temperature and precipitation, with specific reference to their annual course. These phenomena play an important role in the hydrologic regime.

3.2 Annual Course of Temperature

Temperature data are based on daily observations of maximum- and minimum temperature. Daily mean temperature is computed from the mean of daily maximum and minimum. Fig. 1.4 shows the monthly mean temperature (1951-1968) of the valley station St.Jakob (1192 m)/*(San Giacomo)* in the centre of the upper-Ahr valley (see figure 1.1). It varies between -3 °C in January and +17 °C in July. Mean daily maximum temperature varies between 0 °C in January and +22 °C in July, and the mean daily minimum temperature varies between -6 °C and +12 °C.

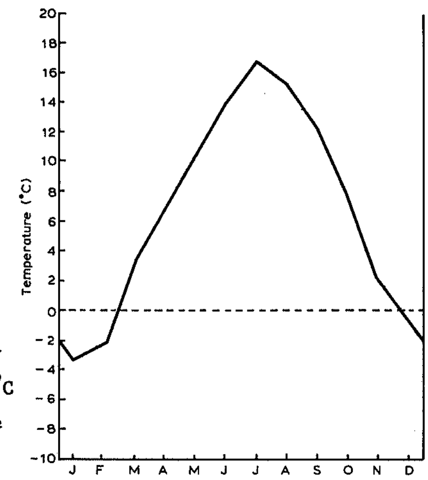


Fig. 1.4 Mean monthly temperature for St.Jakob (1192 m), upper-Ahr valley (Period 1951-1968)

3.3 Annual Course of Precipitation

Precipitation data are based on daily measurements from the standard rain gauge used by the "Hydrografische Dienst der Provinz Bozen", placed at 1.5 m above the ground surface. The gauge has an orifice area of 2500 cm^2. Mean annual precipitation at St.Jakob over the period 1953-1975 amounts to 826 mm. Monthly precipitation reaches its maximum (120 mm) in July and its minimum (38 mm) in March (fig. 1.5).

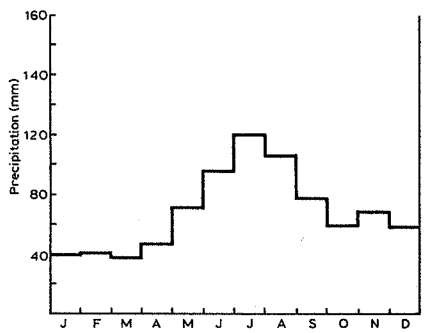


Fig. 1.5 Mean monthly precipitation at St.Jakob (1192 m), upper-Ahr valley (Period 1953-1975)

4 HYDROLOGY

4.1 Snow-cover Cycle

The cyclic process of snow accumulation and melt is characteristic of an Alpine climatic regime. The accumulation and melt regime is presented graphically in fig. 1.6, and shows the annual cycle of the snow line elevation based on observations from 400 stations in the Italian Alps over the period 1939-1959, analysed by Bonanate (1970), and additional data from six stations in the Ahr valley and its immediate surroundings (indicated in figure 1.6). The accumulation limb of the cycle in the Ahr valley seems to be several hundred meters below the average found by Bonanate for the Italian Alps; the melting limbs are comparable.

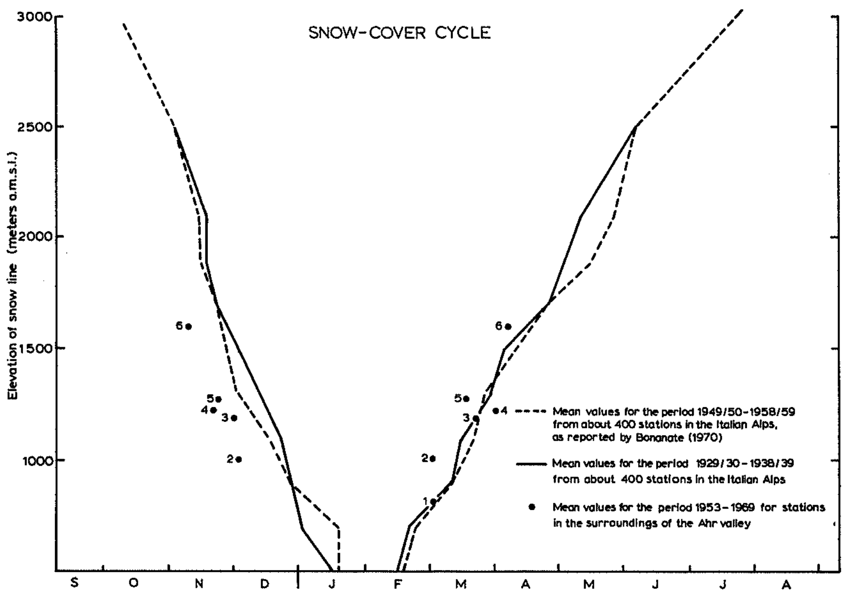


Fig. 1.6 The annual cycle of snow-line elevation, based on observations of 400 stations in the Italian Alps during the period 1939-1959, analysed by Bonanate (1970), and data of six stations in the surroundings of the Ahr valley

1 = St.Lorenzen (813 m); 2 = St.Johann (1011 m); 3 = St.Jakob (1192 m); 4 = Antholz (1236 m); 5 = Mühlbach (1278 m); 6 = Rain in Taufers (1600 m).

4.2 Glaciers

The glaciers in the upper-Ahr catchment have a total surface area of 4.65 km^2, which is 3.1% of the catchment, based on data from 1958 (Comitato Glaciologico Italiano, 1962). The glaciers are concentrated in the south-eastern part (fig. 1.7) and are exposed to the north-west. The largest upper-Ahr valley glacier, the Auss. Lahner Kees with a length of almost

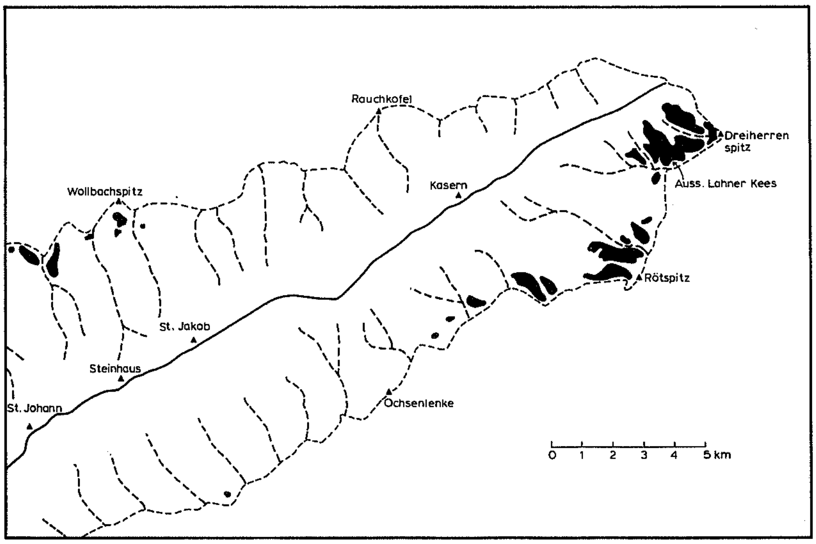


Fig. 1.7 The distribution of glaciers in the upper-Ahr valley (From Hannß, 1967)

3 km, extends from the very pronounced and relief-rich Dreiherren Massif. The dimensions of the glaciers gradually decrease towards the west.

According to the definitions used by the "Comitato Glaciologico Italiano" (1962) two types of glaciers occur in the upper-Ahr catchment. These are:

- **Valley glaciers**. Glaciers with enough accumulation for the tongues to reach from the areas of accumulation *(firn)* into the valleys.
- **Cirque glaciers**. Glaciers whose extent is restricted to the higher flat areas, surrounded by steep head-walls *(cirques)*. During the last 50 years, many Alpine glaciers lost their tongues and degenerated into such glaciers.

4.3 Hydrological Regimes

The regime of runoff from Alpine catchments is characterized by the Alpine climate and the Alpine relief. Dependent on the elevation and the local climate, the following regimes can be distinguished (see also fig. 1.8):

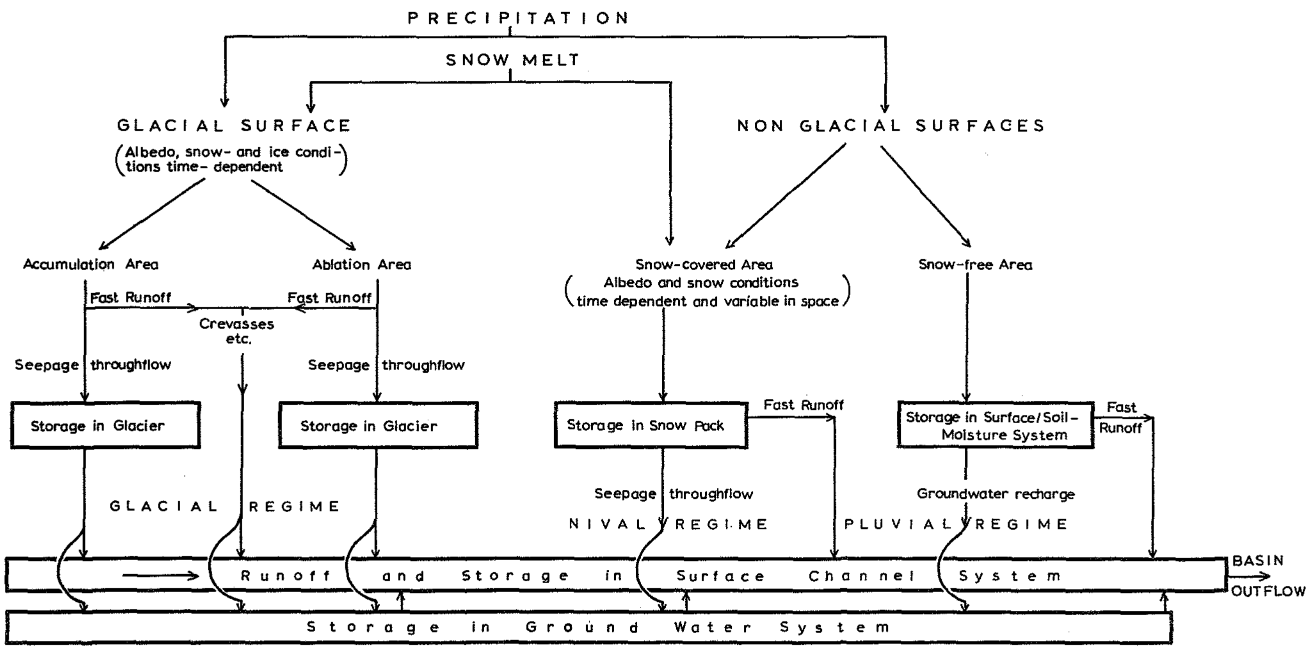


Fig. 1.8 *Schematic representation of system components active in the creation of runoff in a pluvio-nivo-glacial Alpine catchment*

1. **Nival regime**, consisting of runoff from water stored in the snow pack and direct snow-melt.
2. **Glacial regime**, consisting of runoff from glaciers.
3. **Pluvial regime**, consisting of runoff from precipitation.

The three regimes play a combined role throughout almost the entire year. However, their magnitudes and partial contributions to the total regime are related to the time of the year, while the transition from one regime to another is gradual. The variations of the (partial-) correlation coefficients (fig. 1.9) between monthly runoff and monthly mean temperature (A) and between runoff and monthly precipitation (B) reflect very well the seasonally-dependent nature of the different regimes in the Alpine Ahr catchment.

4.3.1 The Nival Regime

During spring the runoff of the river Ahr is governed by the nival regime which is in turn closely related to the snow-cover cycle of figure 1.6. The isotherm of 0 ^{o}C reaches the lower parts of the area in March and snow melt starts, resulting in a gradual increase of snow-melt runoff during spring and early summer. The characteristic daily course of the nival regime is shown in fig. 1.10.

During the melt season, physical changes within the snow pack govern the melting process (U.S. Army Corps of Eng., 1956) as well as the drainage properties of the snow pack (Hoeck, 1952). An overview of the complex factors that effect the runoff from snow melt has been presented by Garstka (Garstka et al., 1958; Garstka, 1964). A special symposium was held in 1972 on the role of snow and ice in hydrology (IAHS, 1972), and resulted in considerable information concerning recent research results on snow properties and processes. The accumulation and ablation regimes of snow bodies in the Rocky Mountains - which are, regarding their relief energy, morphology and snow regime, comparable with the Alpine catchment of the river Ahr - has been described by Engelen (1972), with special reference to their physical properties. He described typical regime curves throughout the accumulation/ ablation-period and found a continuous increase in density throughout this period (fig. 1.11), which is the result of compaction during accumulation and the result of the ripening process during ablation. Comparable phenomena have been reported by Martinec (1965).

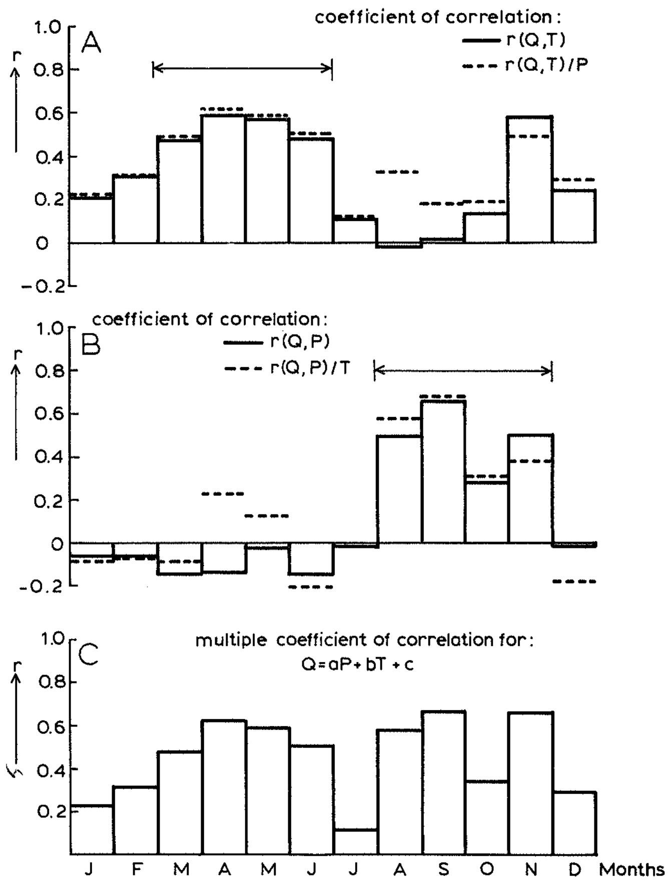


Fig. 1.9 Coefficients of correlation between monthly runoff (Steinhaus), monthly mean temperature (Antholz) and monthly precipitation (St.Jakob), based on the period 1953-1975

A ——— *Between runoff (Q) and temperature (T) - r(Q,T)*
- - - - *Partial correlation corrected for precipitation (P) - r(Q,T)/P*

B ——— *Between runoff and precipitation - r(Q,P)*
- - - - *Partial correlation corrected for temperature - r(Q,P)/T*

C ——— *Multiple correlation coefficient between Q (dependent variable) and P and T*

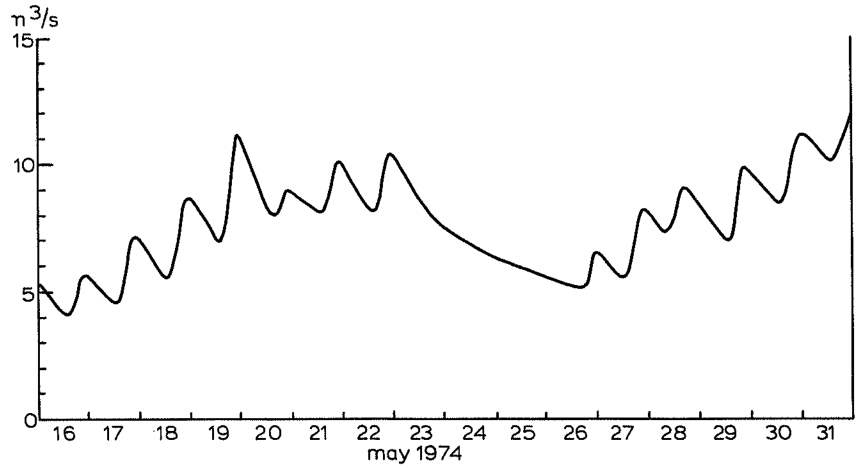


Fig. 1.10 Characteristic daily course of runoff of the river Ahr at Steinhaus, during a period of mainly snow-melt in spring (May, 1974)

From investigations by Hoeck (1952) it appeared that the discharge from snow melt is significantly retarded until the retention capacity of the snow pack has been exceeded. The snow pack thus acts as a capillary zone, which drains only that part of the melting water which is in excess of the retention capacity.

As a result of the large elevation ranges in the study area (see the hypsometric curve of fig. 1.2) the processes of melting, ripening, saturation and drainage will be concentrated in more or less parallel zones, shifting upwards during the melt season (fig. 1.12). The transitions may have a considerable areal extent. Fluid precipitation also influences the situation and may contribute to the ripening process (Garstka, 1964) as well as to the realization of the "field capacity". However, because of the high ratio of latent heat of fusion and heat capacity of water, the heat input from rain can be neglected (Wilson, 1941).

A combination of the snow-cover cycle (fig. 1.6) and this process of a shifting ripening and melting zone is visualized in schematic form by figure 1.13. The indicated vertical extent *(extent of the melting and draining snow pack)* and the horizontal extent *(duration of the active draining period)* are fictitious, and may change considerably from one year to another.

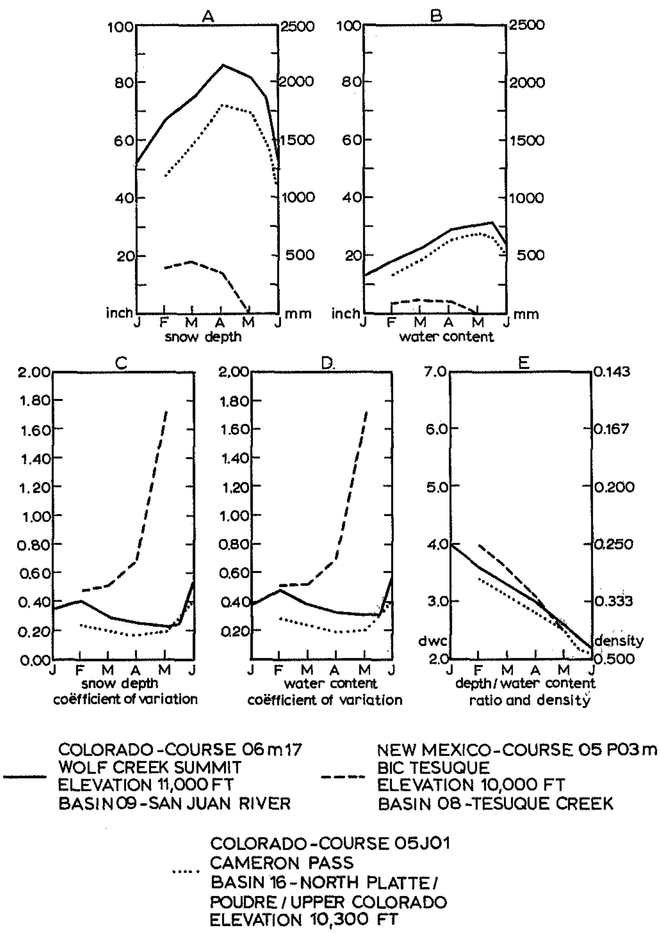


Fig. 1.11 Regime curves of snow-depth and water content in a high mountain snow-cover in the Rocky Mountains, U.S.A. (From Engelen, 1972)

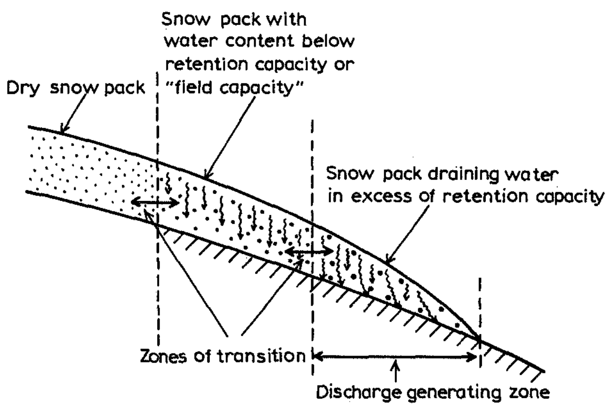


Fig. 1.12 The distribution of snow conditions in a sloping mountain snow pack

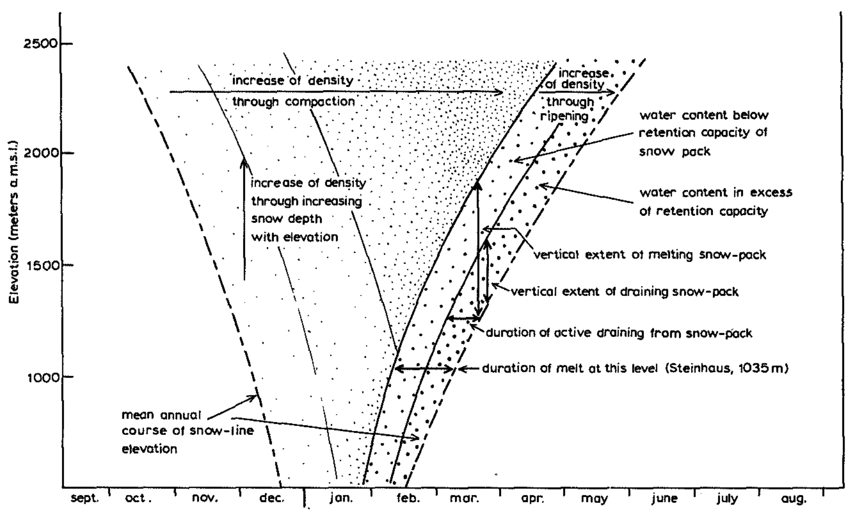


Fig. 1.13 Spatial and temporal distribution of mean snow conditions in a mountain snow pack. The left part (fine speckles) indicates the accumulation period which is elongated in higher elevations. The right part (course speckles) indicates the ablation period, which is about the same length at each level (for explanation see text)

The importance of the snow-melt process for the discharge regime curve is shown in fig. 1.14, and can be explained very well from the mean snow-cover cycle in combination with the hypsometric curve of the catchment (fig. 1.2). About February the snow melt starts in the lower parts of the valley, resulting in a very gradual increase of the discharge, while on the higher parts the accumulation of snow continues. This condition lasts until the end of April when the discharge approximately equals the effective areal precipitation. About this time the total storage of snow in the catchment reaches its maximum value and is concentrated, according to the hypsometric curve, on the flattest parts of the catchment. As a result of the smaller vertical extent of this part of the catchment, the total maximum storage at the end of April melts in a one or two month period (May and June) which explains the very steep increase of the discharge regime curve in this period (figure 1.14). When at the end of June the snow line has retreated to the 2700 m

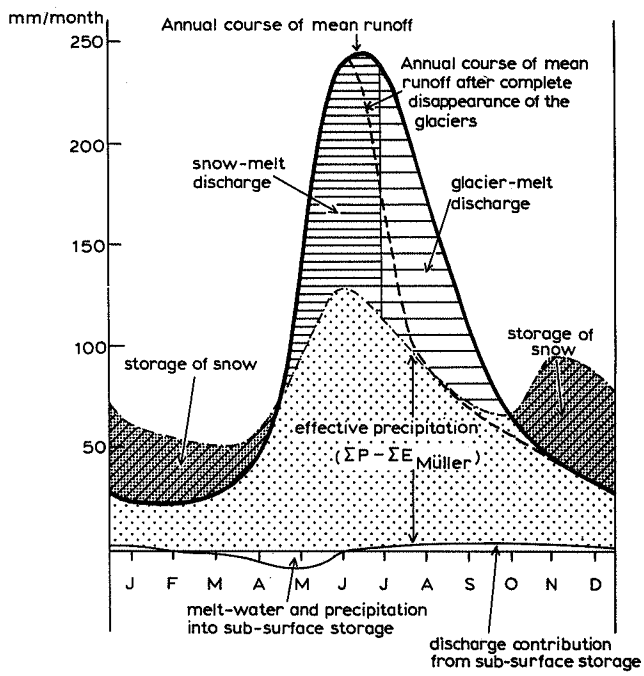


Fig. 1.14 Annual course of mean runoff and water-balance components of the river Ahr catchment (For explanation see text)

elevation line and the snow cover is reduced to about 15% of the catchment, concentrated on the higher and steeper parts, the discharge regime curve starts to fall. The discharge however still exceeds the areal precipitation as a result of glacier melt.

The highest daily discharges of the nival regime occur in June, when a relatively warm period is preceeded by a longer period of relatively low temperatures, leaving the snow line in the lower regions.

4.3.2 The Glacial Regime

The magnitude of the glacial regime is governed by the annual course of temperature, with its minimum in winter and its maximum in summer. During spring, the role of the glacial regime is initially small but increases as summer approaches and the role of the nival regime decreases. The highest daily melt runoff occurs at the end of June due to the combined effect of the glacial regime and the nival regime.

The glacial regime is delayed one or two months with respect to the nival regime and starts to flow at about the time when that from the nival regime starts to decrease. Maximum glacier melt occurs in July and August when the temperature is high and the glacier tongues are free from snow and the glacier ice with its low albedo (about 40% against 80% for freshly fallen snow, Dreiseitl, 1973) is at the surface.

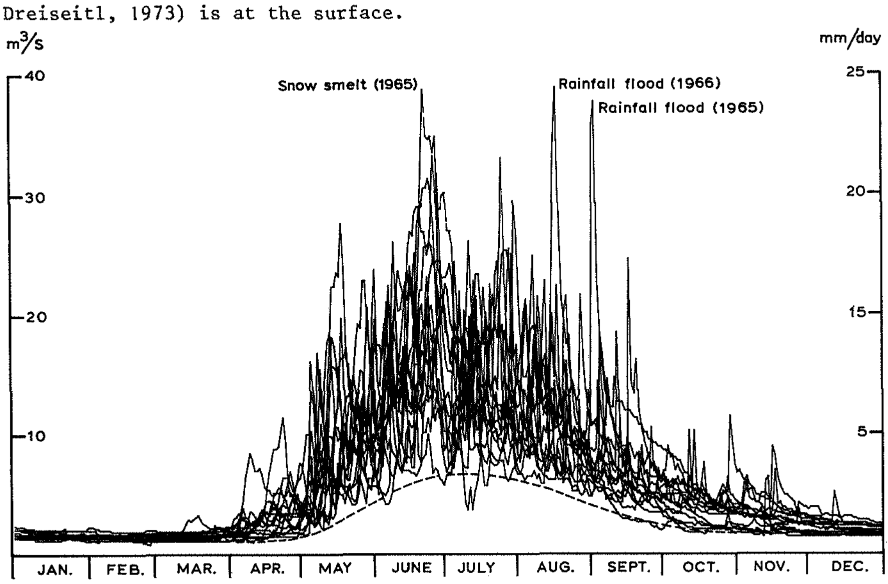


Fig. 1.15 Plot of 22 annual hydrographs of daily discharge of the river Ahr at Steinhaus (Period 1953-1974)

Both the nival and the glacial regime sustain a continuously high level of discharge throughout the summer season and so prevent the river from low levels during warm and dry summer periods. Fig. 1.15 shows a plot of 22 annual hydrographs of daily discharge, in which the lowest discharges are bounded by a *"minimal discharge curve"* which, when compared with the mean daily effective precipitation (3.6 mm in July), is extremely high.

Runoff from glaciers in relation to the weather elements has been investigated a.o. by Lang (1967, 1968, 1971) and by Martinec (1960, 1965, 1970). During fine weather conditions, the character of discharge from the glacier system is of sinusoidal form with a growing amplitude until a stationary situation is reached if favourable melting conditions continue. During such periods the base flow from the other systems gradually decreases. Fig. 1.16 shows a typical hydrograph of a fine weather period in July following a period of rain.

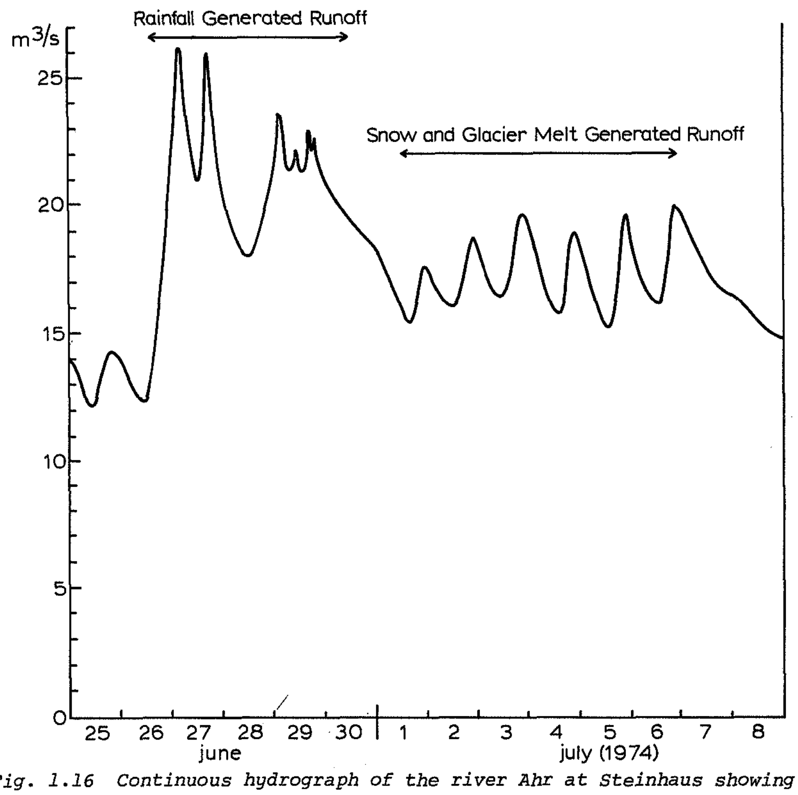


Fig. 1.16 Continuous hydrograph of the river Ahr at Steinhaus showing the short-term change in runoff contribution from the pluvial system (Rainfall Generated Runoff) to that from the nivo-glacial system (Snow and Glacier Melt Generated Runoff), June-July 1974

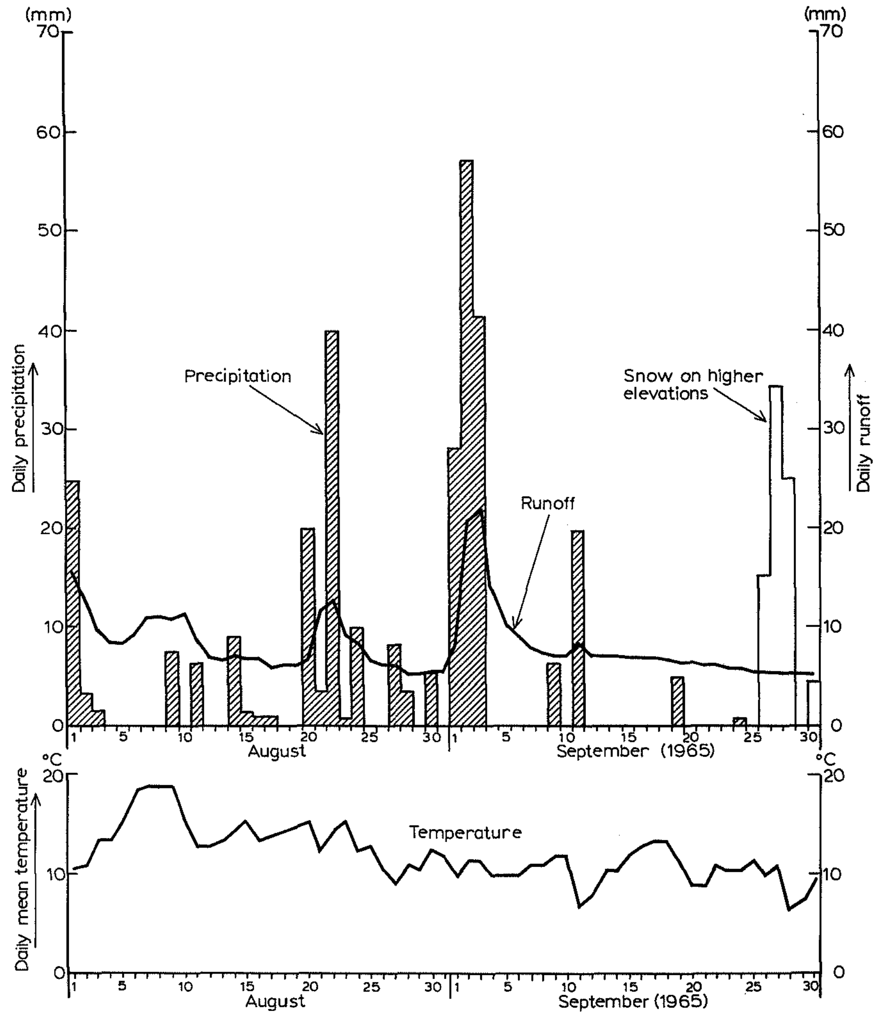


Fig. 1.17[a] *The course of precipitation (St.Jakob, 1192 m) and temperature (Antholz, 1236 m) during an extreme runoff occurrence of the river Ahr in 1965, gauging station Steinhaus*

4.3.3 The Pluvial Regime

Although the melt regimes are responsible for the bulk of the yearly runoff, the pluvial regime is responsible for extreme flood occurrences, usually occurring in late summer (August and September). Examples of extreme floods

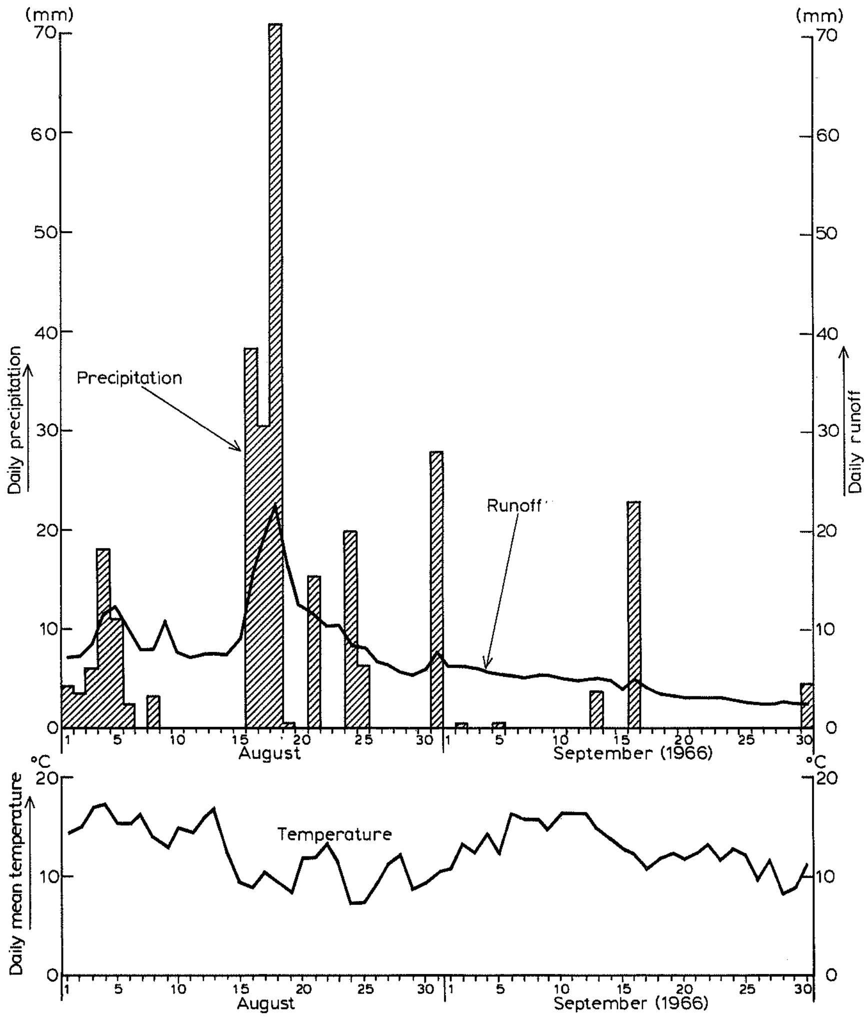


Fig. 1.17[b] *The course of precipitation (St.Jakob, 1192 m) and temperature (Antholz, 1236 m) during an extreme runoff occurrence of the river Ahr in 1965, gauging station Steinhaus*

are those from 1965 and 1966 (fig. 1.15 and fig. 1.17, a & b), created during severe thunder storms and continuing cloud bursts, which led to tremendous damage by mass-movements, land-slides and debris flows (Engelen, 1967, 1968) and extreme runoff occurrences all over Southern Tyrol (Tröschl, 1967).

4.4 The Water Balance

4.4.1 Problems with Respect to the Water Balance

The computation of a water balance for a high mountain catchment, where a large part of the annual precipitation falls as snow, is even more difficult when glaciers take part. One of the major problems is the estimation of areal precipitation. The measurement of "*true*" rain is difficult, since different types of gauge give differences in catch of up to 15% (Bull, 1960). The measurement of snowfall is even more difficult as a result of wind effects, enhanced by the lower specific weight of snow particles and the displacement of already fallen snow (Hoinkes, 1957). Extensive investigations on this subject have been performed a.o. by Grunow (1953) and by Hoinkes (1962). Grunow investigated the influence of the inclination of the rim of the gauge and found large differences in catch with different inclinations (see also Kubat, 1972). Hoinkes and Lang illustrate the fact that totalizors, which are frequently used in elevated and remote areas, catch only 45% to 60% of the equivalent snow which falls in the direct surroundings of the site. From extensive observations in the USSR (W.M.O., *1970*) corrections for wind effects were estimated to be 10-15% for rain and 40-60% for snow, using 200 cm^2 orifice gauges installed 2 meter above the ground surface. Another problem with respect to the estimation of areal precipitation arises from the fact that in most areas gauging stations are restricted to valley sites, and that data from higher regions are scarce. Also, the effect of horizontal interception of fog by vegetation (Grunow, 1964a) and from clouds moving across mountain ridges may in some cases form a considerable part of the total input of water into the catchment (Grunow & Tollner, 1969; Ward, 1974; Vischer & Sevruk, 1975).

The second problem with respect to estimation of the water balance is the valve of areal evapotranspiration. For catchments without glaciers the areal evapotranspiration may be estimated by considering it as the residual term in the water-balance equation if discharge is measured and the areal precipitation is estimated from gauging stations spread over the catchment. However, this method can only be applied in catchments which contain glaciers if the change in storage of the glaciers can be estimated with sufficient precision.

In the following expression the glacier storage is taken as the residual term in the water balance, since this term cannot be estimated directly.

The long-term water-balance equation, neglecting changes in storage of soil moisture and ground water, therefore has the form:

$$\overline{\Delta S} = \frac{1}{m}\left(\sum_{n=1}^{m} P_n - \sum_{n=1}^{m} Q_n - \sum_{n=1}^{m} E_n\right) \qquad (1.1)$$

where, $\overline{\Delta S}$ = mean annual change in storage of the glaciers
P_n = areal precipitation during the n^{th} year
E_n = areal evapotranspiration during the n^{th} year
Q_n = discharge from the catchment during the n^{th} year
m = number of years

4.4.2 Estimation of Areal Precipitation

The relation between elevation and mean annual precipitation, compiled from several stations in the Ahr valley and its immediate surroundings, is shown in fig. 1.18 based on the period 1953-1975. This relation has been used to estimate the mean areal precipitation for each month, assuming that the relation is valid throughout the year.

The mean elevation of the upper-Ahr catchment from the hypsometric curve (fig. 1.2) is 2160 m and corresponds to an annual areal precipitation of 1300 mm. This amount has been distributed over the months of the year in accordance with the observed record at St.Jakob (fig. 1.5).

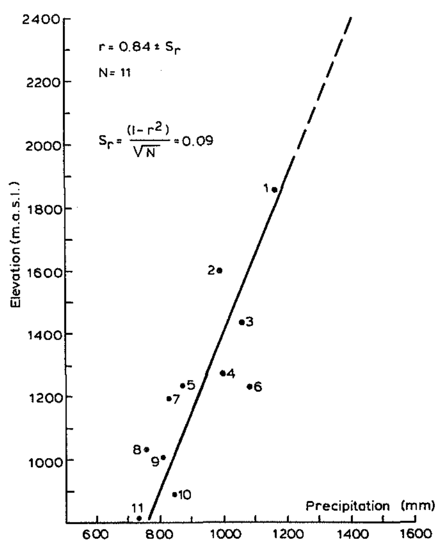


Fig. 1.18 The relation between elevation and annual precipitation for 11 stations in the surroundings of the Ahr valley over the period 1953-1975

1 = Neves; 2 = Rain in Taufers; 3 = Lappach; 4 = Mühlbach; 5 = Antholz; 6 = Mühlwald; 7 = St.Jakob; 8 = Rasen; 9 = St.Johann; 10 = Sand in Taufers and 11 = St.Lorenzen

4.4.3 Estimation of Areal Evapotranspiration

Evapotranspiration is frequently computed from the water balance by including it as the residual term, but the haphazardous measurement of precipitation as a result of snow redistribution, the type of rain gauge used and the low density of the gauging network in high-mountain Alpine catchments, prohibit such an application. Given the necessity to insert evapotranspiration as a known term in the water balance of glaciated areas, as argued above, a direct estimation of areal evapotranspiration must be made.

For the estimation of potential evapotranspiration many computational methods exist, some of which are based on energy considerations (e.g. Penman, 1948, 1956, 1963) and others, based on empirical relationships (e.g. Thornthwaite, 1942; Jensen & Haise, 1963) (see W.M.O., 1966). For the estimation of actual evapotranspiration from potential evapotranspiration, reduction factors are being used, based on empirical relationships (e.g. Blaney and Criddle, 1950). For Alpine circumstances, some formulas are better suited than others (see Hounam, 1971), but the main problem for Alpine areas arises from the variety of circumstances for evaporation to occur in relation to the vertical extent, exposure and snow cover.

Very accurate measurements on snow evaporation *(sublimation)* and condensation have been performed by Köhler in 1920/21 at the Haldde Observatory (Norway), using a balance with a very high sensitivity, though the results were published many years later (Köhler, 1950). Lauscher (1978) has recently demonstrated the existence of a winter balance between sublimation and condensation using Köhler's data. Decisive for the condensation is the water content of the advected air. A comparison of Köhler's measurements with the formula developed by Kuzmin (1953) - recommended for application by W.M.O. (1966) - shows very good agreement and supports the very low annual mean daily evaporation of 0.052 mm/day for the firn areas near Sonnblick, as computed by Lauscher et al. (1976).

For the estimation of areal evapotranspiration of the upper-Ahr valley, with an elevation range of 1000-3500 m, the two stations St.Johann (1011 m) and St.Jakob (1192 m), with only temperature and precipitation measurements, are inadequate. Therefore, use is made of annual and monthly evapotranspiration data from Alpine catchments at different elevations, based on direct computations and water-balance computations performed separately by W. Müller, H. Steinhäusser and E Reichel.

Computations by Müller

Using the method of Albrecht (1951) for computation of evapotranspiration in summer periods (without snow cover), based on climatic data and surface temperatures, and the method of Sverdrup (1936) for the sublimation of snow for the periods with snow cover, Müller (1964, 1965) estimated mean monthly and annual evaporation at three Alpine stations at elevations of 1200, 2000 and 2500 m (table 1.1 and fig. 1.19).

Table 1.1 Mean monthly evapotranspiration (1901-1941) at three elevations, computed by Müller (1965), based on Albrecht's method for snow free periods and Sverdrup's method for sublimation (in mm)
* Areal evapotranspiration estimated in combination with the hypsometric curve

	E L E V A T I O N			
	1200 m	2000 m	2500 m	*Ahr Valley
January	1.5	3.5	2.9	2
February	6.0	3.0	3.2	4
March	14.1	4.3	0.0	4
April	23.3	13.4	-1.2	8
May	47.2	18.4	8.3	14
June	69.7	33.8	9.8	21
July	83.8	87.1	51.3	74
August	82.8	78.4	75.0	76
September	53.2	56.2	47.1	50
October	32.5	30.6	13.3	22
November	9.4	7.3	5.9	5
December	3.4	1.6	1.8	2
Year	426.9	337.8	217.4	282

Computations by Steinhäusser

From long term water-balance analyses of 29 Alpine catchments, carried out by Steinhäusser (1952, 1967, 1969, 1971), it appears that there is a distinct relation between annual evapotranspiration and mean elevation (see fig. 1.20).

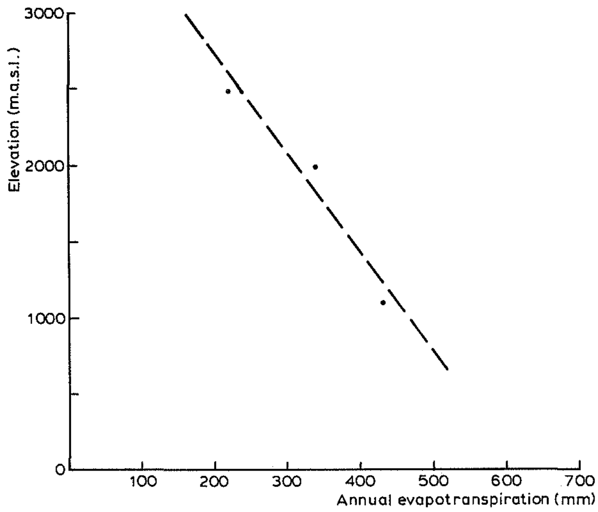


Fig. 1.19 Estimation of actual mean annual evapotranspiration (1901-1941) at three elevations in the Alpine region, based on Albrecht's method for snow free periods and Sverdrup's formula for sublimation (After: Müller, 1965)

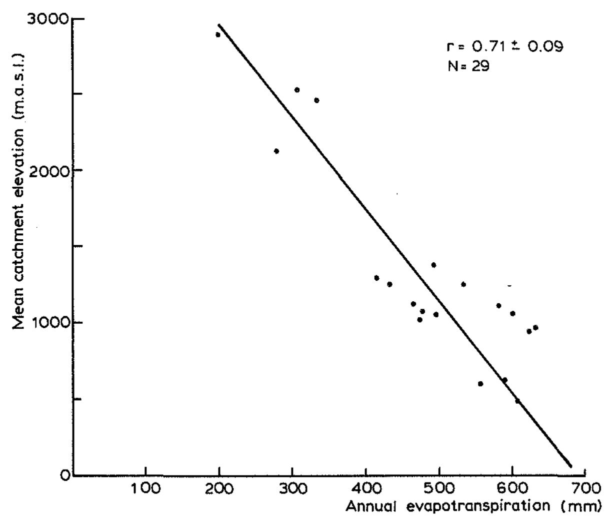


Fig. 1.20 The relation between mean annual evapotranspiration and mean catchment elevation, based on data from Austrian discharge areas (After: Steinhäusser, 1969)

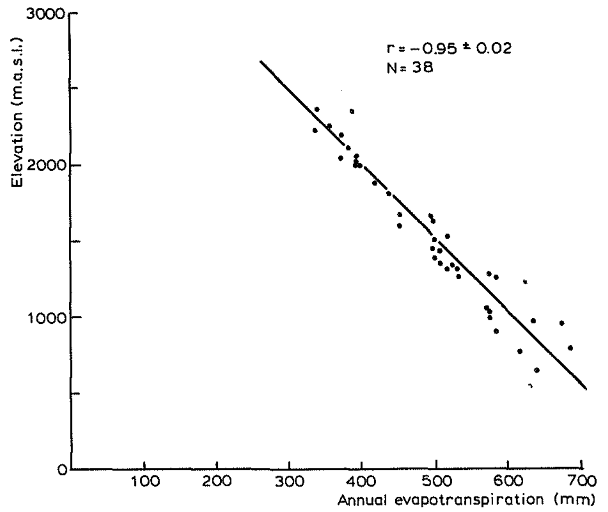


Fig. 1.21 The relation between mean annual evapotranspiration and mean catchment elevation, based on data from discharge areas in the north-western and northern Swiss Alps (Compiled from data after: Reichel, 1957)

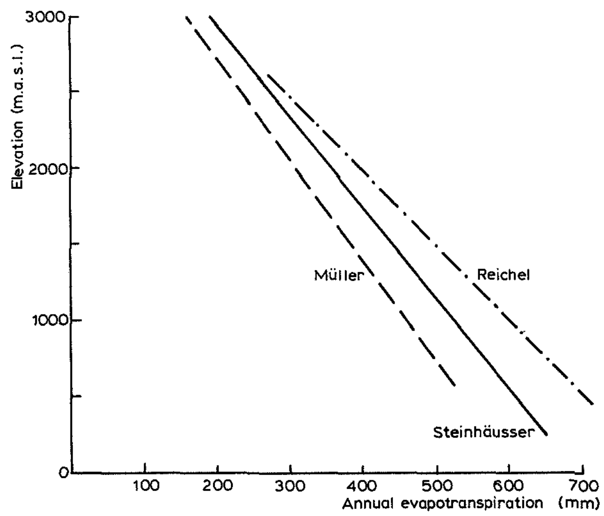


Fig. 1.22 Comparison of the relations between evapotranspiration and elevation as found by Steinhäusser (Austrian Alps), Müller (Austrian Alps) and Reichel (north-western and northern Swiss Alps)

Computations by Reichel

Reichel (1957) has compared evapotranspiration values estimated according to the method proposed by Wundt (1937) with values computed from the water balance. The need to introduce correction factors for Wundt's method, which is based on mean precipitation and temperature, has already been shown by Steinhäusser (1952) and Kern (1954). After application of correction factors, Reichel has made new estimations of annual evapotranspiration in 38 Alpine catchments in relation to altitude and annual precipitation as shown in fig. 1.21.

A comparison of the results found by Müller with those found by Steinhäusser shows a fair agreement between directly computed and estimated evapotranspiration from the water balance (fig. 1.22). The results computed by Reichel show higher values, which is explained by the fact that the catchments he compared are concentrated in the north-western and northern Swiss Alps and have physiographic conditions which are different from those of the Austrian Alps, characterised by a different annual distribution of precipitation (Fliri, 1974) and more effective foehn winds in the northern part.

Table 1.2 Long-term mean monthly water-balance components of the upper-Ahr catchment over the period 1926-1943 and 1953-1975, neglecting monthly changes in storage of soil-moisture and ground-water

$\overline{P}$ = mean monthly precipitation; $\overline{Q}$ = mean monthly runoff; $\overline{E}$ = mean monthly evapotranspiration; $\overline{\Delta S}$ = mean annual change in storage of the glaciers.

	$\overline{P}$	$\overline{Q}$	$\overline{E}$	$\Sigma\overline{P}$	$\Sigma\overline{Q}$	$\Sigma\overline{E}$	$\Sigma\overline{Q} + \Sigma\overline{E}$	$\Sigma\overline{P}-(\Sigma\overline{Q}+\Sigma\overline{E})$
November	107	54	5	107	54	5	59	38
December	48	38	2	155	92	7	99	56
January	50	28	2	205	120	9	129	76
February	55	24	4	260	144	13	157	103
March	74	28	4	334	172	17	189	145
April	88	42	8	442	214	25	239	203
May	130	132	14	552	346	39	385	167
June	147	267	21	699	613	60	673	26
July	181	256	74	880	869	134	1003	-123
August	167	184	76	1047	1053	210	1263	-216
September	129	116	50	1176	1169	260	1429	-253
October	124	78	22	1300	1247	282	1529	$\overline{\Delta S}$ = -229
Σ	1300	1247	282					

On the basis of the results found by Müller (table 1.1), long-term mean monthly and mean annual evapotranspiration has been estimated for use in the present long-term water-balance computations (table 1.2).

Mean monthly values of effective precipitation, i.e., the difference between estimated areal precipitation and estimated areal evapotranspiration (P-E), were used for the compilation of the overal regime curve shown in fig. 1.14.

4.4.4 The Change in Ice Mass of the Glaciers

The majority of Alpine glaciers have long been in a retreat phase (Finsterwalder, 1953; Hoinkes, 1953, 1968; Patzelt, 1970; Kasser, 1973). In order to estimate the change of ice mass of the glaciers in the upper-Ahr catchment, a long-term water balance has been computed from eq. 1.1 using estimated areal precipitation and evapotranspiration data as derived above and given for the selected period in table 1.2.

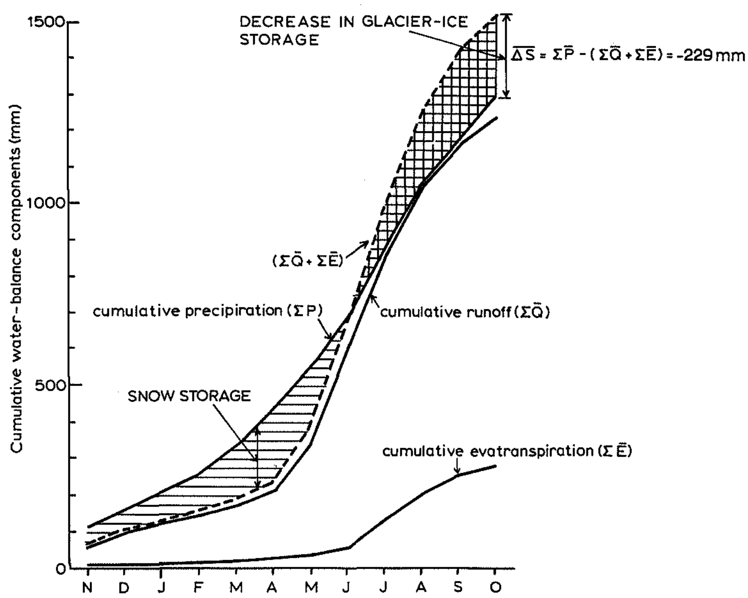


Fig. 1.23 Long-term annual water-balance components (cumulative) of the upper-Ahr catchment over the period 1926-1943 and 1953-1975

$\overline{P}$ = mean monthly precipitation; $\overline{Q}$ = mean monthly runoff; $\overline{E}$ = mean monthly evapotranspiration; $\overline{\Delta S}$ = mean annual change in glacier-ice storage;

Figure 1.23 shows the terms of the water balance in cumulative form during the hydrological year which runs from November till October in Alpine catchments. The magnitude of $\overline{\Delta S}$ should equal the mean change of ice mass in mm/year during the 41-year period. The computed mean annual value of $\overline{\Delta S}$ is -229 mm as a layer over the whole catchment, which corresponds to a layer of 7.3 m of water spread over the glacier surface of 4.65 km^2. However, this value is thought to be considerably overestimated, probably as a result of underestimation of precipitation at higher elevations. This is explained by the fact that no precipitation data are available from elevations above 1600 m, 560 m below the mean catchment elevation. Moreover, the effect of horizontal interception of fog from clouds crossing the mountains (Grunow, 1964a) and condensation at the snow and glacier surfaces will be of increasing importance at higher elevations (Lauscher, 1978).

Nevertheless, high ablation rates have been reported by Hoinkes (1953) on the "Horn Kees", a glacier in the Zillertaler Alps. During a 25-year period the surface of this glacier, somewhere on the snout, melted vertically with a mean annual rate of 2.4 meter from 2320 to 2260 m. He also measured mean daily ablations of 43 mm on the snout during a 7-day period. Comparable high ablation rates have been reported by Lang (1967).

The lowering of glacier surfaces during the period 1920-1950 is shown in fig. 1.24 as a function of altitude. These data, as presented by Finsterwalder (1953), are based on observations of 8 glaciers in the Zillertaler, Stubaier and Ötztaler Alps. The lowering varies from about 4 m near the snouts (± 2000 m) to zero in the firn areas (± 3400 m).

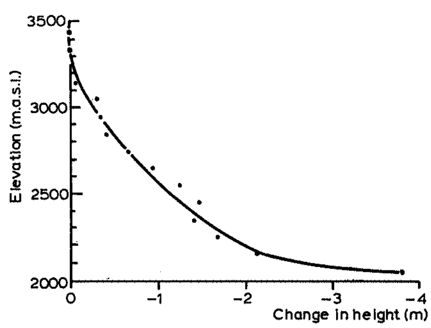


Fig. 1.24 Mean annual change in height (m) averaged from 8 glaciers in the Eastern Alps, as a function of elevation, over the period (1920-1950) (After: Finsterwalder, 1953)

An estimate of the mass change of the upper-Ahr glaciers, using the relation given in fig. 1.24, gives an annual change of 0.8 m as a layer over the glacier surface, which is indeed considerably different from the value estimated from the water balance (7.3 m).

Although the change of ice mass as computed from the water balance may be overestimated, the retreat generally follows measurements of the snouts of larger glaciers in the upper-Ahr valley published by the Comitato Glaciologico Italiano (1962) (see table 1.3). Three of the larger glaciers retreated their snouts at a rate of about 10 m/year during a period of nearly 30 years. The occurrence of this phenomenon on a much larger scale is illustrated by fig. 1.25, which shows the variations in position of glacier fronts in the Italian Alps. The majority of glaciers are in retreat, though some are stationary and some are even in advance. Comparable fluctuations of the glacier fronts occurred in the Eastern Alps and in the Swiss Alps (see fig. 1.26).

Glacier fluctuations such as the period of advance about 1920 and the gradual retreat of the majority of the glaciers since 1925, are governed by regional and even very local climatic changes resulting from changes in the general circulation. These are clearly shown by Hoinkes (1967, 1968, 1970, 1971). This explains the fact that on a regional scale and even within

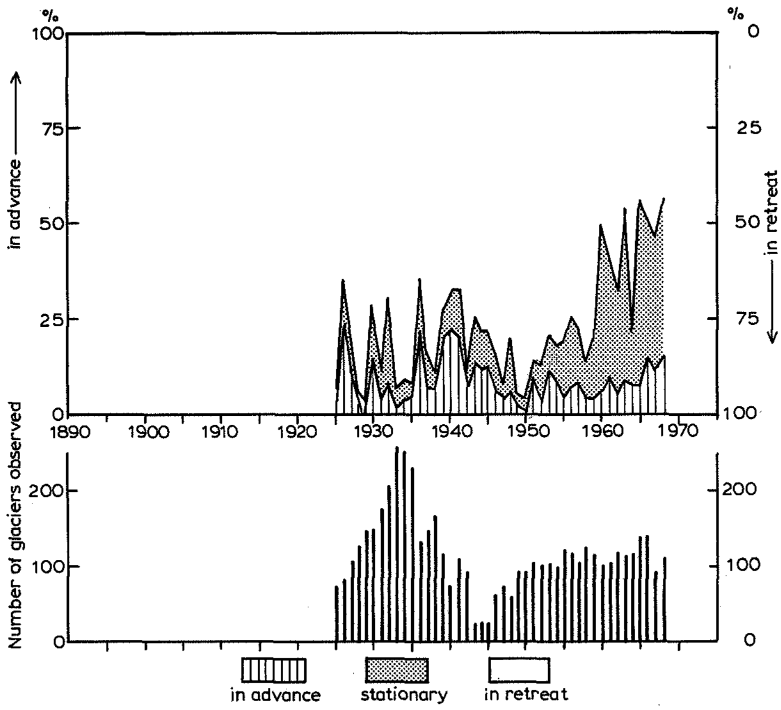


Fig. 1.25 Percentage of glaciers in advance, stationary or in retreat in the Italian Alps during the period 1925-1968 (Compiled from data retrieved from Kasser, 1973)

Table 1.3 Main characteristics of glaciers in the upper-Ahr catchment[1]

Glacier	Surface[2] (km^2)	Exposi- tion	Length[2] (m)	Highest[2] Point (m a.s.l.)	Lowest[2] Point (m a.s.l.)	Retreat of Snout: Period	Retreat of Snout: Retreat (m)	Retreat of Snout: Retreat per Year (m)	Identification[3]	Type[4]
Wollbach Kees	0.11	S	300	2950	2780				910[b]	2
Prettau Kees	0.56	N.NW	1625	3085	2480	1930-1958	310	11.1	912	1
Äuss. Lahner Kees	1.32	NW	2820	3499	2285	1930-1958	270	9.6	913	1
Kerra Kees	0.17	NW	1075	3110	2585	1927-1957	272	9.1	914	2
Windtal Kees	0.13	SW	380	3065	2845				916	2
Südl. Windtal Kees	0.27	NW	1250	3100	2480				919	1
Rechts Röt Kees	0.72	NW	1900	3220	2520				920	1
Links Röt Kees	0.32	W	1480	3460	2680				921	1
Rötfleck Kees	0.52	NW	1000	3000	2580				922	2
Merb Kees	0.16	N	400	2850	2520				923	2
Alprech Kees	0.12	NW	300	2900	2700				924	2

(1) Data retrieved from the "Comitato Glaciologico Italiano" (1962), glaciers smaller than 0.1 km^2 have been omitted

(2) Observed in 1958

(3) Identification number according to the "Comitato Glaciologico Italiano" (1962)

(4) Valley glacier (1); Cirque glacier (2)

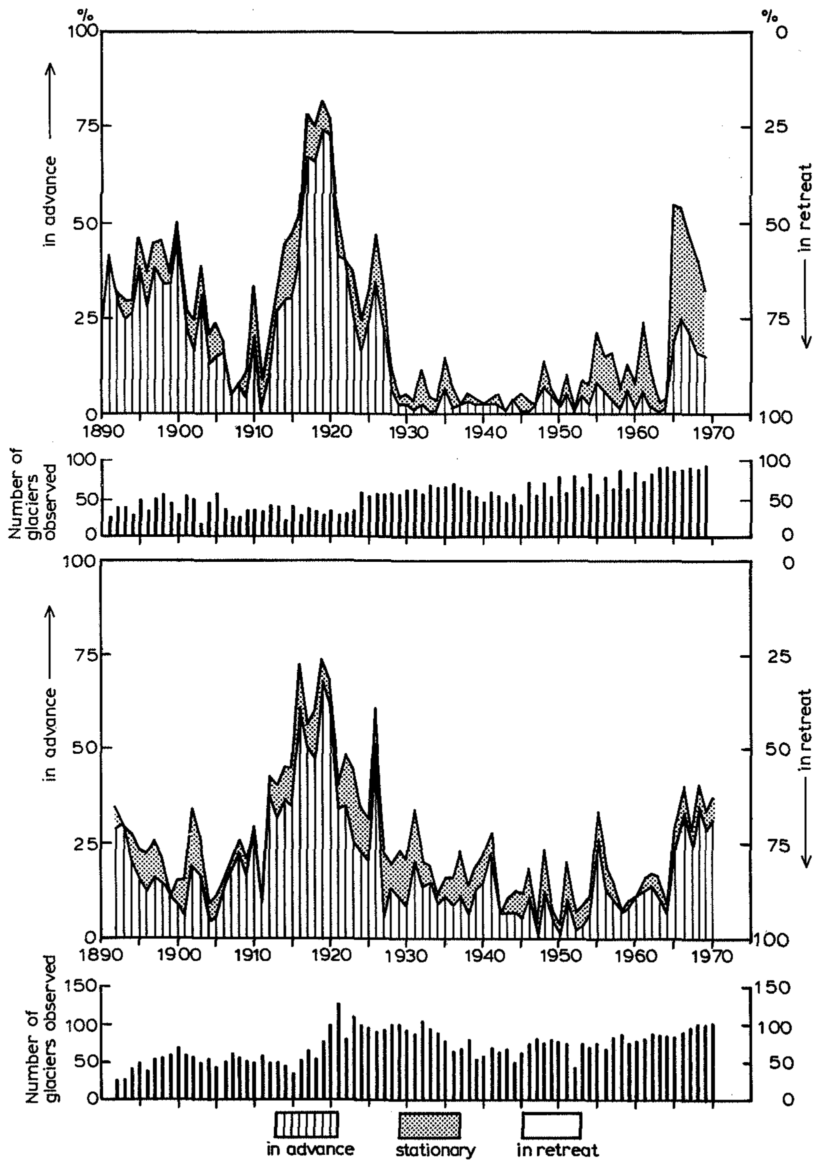


Fig. 1.26 Percentage of glaciers in advance, stationary or in retreat in the Eastern Alps (above) during the period 1890-1969 and in the Swiss Western Alps (below) during the period 1891-1965 (Compiled from data retrieved from Kasser, 1973)

isolated Alpine mountain ranges the fluctuations are not always synchronous (Wilhelm, 1975). Hoinkes (1968) demonstrated the feasability of relating glacier fluctuations to frequencies of particular circulation types for glaciers in Switzerland between 1891 and 1966, by considering seasonal weather characteristics of each type in terms of being favourable and unfavourable to glacier mass budgets. Fliri demonstrated the high correlation between snow fall in summer and glacier fluctuations, which may be explained by the slowing down of the melting process resultant from the high albedo of fresh snow on the snouts, and suggested that the course of the weather in summer is of much more importance for glacier fluctuations than that in winter (Fliri, 1975). Recently Fliri (pers. comm.) found that the summer half-year dictates about 2/3 of the long-term mass-balance changes in the eastern Alps, the winter half-year only 1/3.

4.4.5 Retreating Glaciers and Future Regime of the River Ahr

The reported retreat of glaciers implies important consequences for the regime of many Alpine rivers and is of practical significance for the related operational use of many high mountain artificial lakes for hydro power. With the complete disappearance of the glaciers, part of the regime curve (fig. 1.14) will change into that figured by the dashed line; that is, from the *nivo-pluvio-glacial regime* into the *nivo-pluvial regime*.*

* *From recent measurements it appears that about 75% of the eastern Alpine glaciers are in advance, especially the smaller ones (Fliri, pers. comm.). However, such information is not known from the Ahr valley.*

CHAPTER II

W E A T H E R   T Y P E S

. INTRODUCTION

Until Bergeron (1930) introduced a dynamic approach to climatology by means of weather types (WETTERLAGEN), synoptic meteorology on the one hand and climatology on the other were developed without being related one way or another. Since then, scientific opinion has required a synthesis between both disciplines in order to achieve optimal benefit in a mutual way.

A most important contribution to its realisation was produced by Flohn (1954) who described this synthesis as "Synoptic Climatology" or "Witterungsklimatologie". He suggests a method of describing the total weather process in terms of a succession of different characteristic large-scale weather types or GROSSWETTERLAGEN, as introduced into German meteorology by Baur (1936). His approach contributed much to a better understanding of the geographical distribution of weather conditions during similar large-scale weather types. Investigations on this subject have been performed, amongst others, by Bijvoet and Schmidt (1958), Bürger (1958), Schüepp (1959a), Fliri (1962a, 1962b, 1964a, 1975), Steinhauser (1962).

Synoptic climatology in fact serves a twofold aim:

Firstly, it plays an important role in modern climatology, in which increasing stress is laid upon the development of the weather situation, rather than on the average weather situation itself as a statistical entity, as has traditionally been the case in climatology. Statistical analysis of the occurrence and sequence of principal large-scale weather types in combination with anomalies of meteorological elements has offered the possibility of creating a real dynamic picture of climate (Fliri, 1962a, 1964b; Lauscher, 1954; Schüepp and Fliri, 1966), and also plays an important role in the investigations of climatic fluctuations (see e.g. Dzerdzeevskii, 1966).

Secondly, synoptic climatology may have some prognostic value, though Flohn and Hess (1949) attached little value to the prognostic significance of synoptic climatology because the development of regional weather during one large-scale weather type is fairly ambiguous. On the basis of "Singularities" (that is, a length of time, at most 12 days, during which a certain GROSSWETTERTYP occurs on at least 3 days in succession in more than 2/3 of the cases) they even exclude medium- and long-range weather forecasting because of the discrepancy between the occurrence of large-scale weather types and the development of local weather. Also, Baur (1963) stated that in the temperate zone singularities demonstrate too many exceptions to justify their application in medium- and long-range weather forecasting. However, with the growing importance of computers and mathematical models for computation of air flow patterns several days in advance, synoptic climatology was expected to contribute to short- and medium-range weather forecasting (Schüepp, 1959b; Schüepp and Fliri, 1966). This has been confirmed by Kirchhofer (1971) and Courvoisier (1975).

In order to perform a systematic analysis of hydrologic phenomena during comparable weather types, one is committed to an objective classification of those types. Since the initiation of dynamic climatology by Bergeron in 1930 several classification systems of large-scale weather types have been developed for Europe as well as for other parts of the world, to serve as a basis for a dynamic climatological approach to the weather process.

Before making a choice of classification system for this specific investigation, an overview and evaluation of the existing classification systems must be made. Classification systems for regions outside Europe and those which have hardly passed the state of a proposal, are of no further concern here and for these the reader is referred to the literature (Cehak, 1962; Böer, 1965; Anderson, 1971; Hufty, 1971; Wada et al., 1971; Barry & Perry, 1973).

2 WEATHER TYPE CLASSIFICATION SYSTEMS IN EUROPE

The effective development of synoptic climatology extends back to the years 1941-1943 when, under the leadership of Franz Baur (Baur et al., 1944), a calendar of large-scale weather types in Europe was compiled for the period 1881-1939. In 1936 Baur had already introduced the concept of "GROSSWETTER-LAGEN" (large-scale weather types), defined as the distribution of barometric pressure over a part of the surface of the earth, at least the size of Europe, for a period of several days during which successive weather conditions are more or less characteristic.

Definitions

To avoid confusion over the concept of Grosswetterlagen, some definitions as proposed by Baur (1948, 1963) will first be presented. A precise translation of originally German terms is difficult and German terms will be used if necessary.

WEATHER *(Wetter)* is the directly observable state of the local atmosphere at a given moment or, at most, over a period of twenty-four hours.

WEATHER TYPE *(Witterung)* refers to the basic character of weather conditions over a period of several days, and over a small region.

LARGE-SCALE WEATHER *(Grosswetter)* refers to the basic pattern of weather conditions over a period of several days and over an area as large as Europe.

Since the terminology with respect to the current subject has not been consistently applied in the literature, a consistent terminology is proposed in scheme 2.1 based on a distinction (a) on the areal extent of the area concerned and (b) on the length of the period concerned.

AREAL EXTENT				
LOCAL	REGIONAL	LARGE-SCALE		
LOCAL WEATHER	REGIONAL WEATHER	LARGE-SCALE WEATHER	MOMENT	PERIOD
LOCAL WEATHER SITUATION *(KLEINWETTERLAGE)*	REGIONAL WEATHER SITUATION *(WETTERLAGE)*	LARGE-SCALE WEATHER SITUATION *(GROSSWETTERLAGE)*	DAY	
LOCAL WEATHER TYPE *(KLEINWITTERUNGSLAGE)*	REGIONAL WEATHER TYPE *(WITTERUNGSLAGE)*	LARGE-SCALE WEATHER TYPE *(GROSSWITTERUNGSLAGE)*	SEVERAL DAYS	

Scheme 2.1 Terminology with respect to the weather with reference to the "Areal Extent" and the "Period" of concern. (Note that "GROSSWITTERUNGSLAGE" would be more appropriate to denote Baur's "GROSSWETTERLAGE" which is based on large-scale and several days)

The *Grosswetter* concept was applied by Baur in Europe for **LARGE-SCALE WEATHER TYPES** *(Grosswetterlagen)*. The use of *Wetter* and *Witterung* here is somewhat confusing. Schüepp (1959b, pg. 243) correctly states that *Grosswitterungslagen* instead of *Grosswetterlagen* would be a more appropriate term, since *Witterung* refers to the state of the atmosphere over a period of several days, while *Wetter* refers to its daily state (see scheme 2.1).

2.4

As criteria for the classification of *Grosswetterlagen*, Baur used the geographic position of the steering cyclones and anticyclones as well as the position and distribution of frontal zones. On that basis, a division was initially made in "central high" and "central low" flow systems. The character of the weather was also laid down as being either cyclonic or anticyclonic, with the classification of *Grosswetterlagen* based on the height of the 500 mb level.

A basic problem in designing a classification system are the number of types or classes to be incorporated. These should be weighed against the information that is to be extracted from the classification. This difficulty appears from the fact that in a short time several versions of Baur's system have been compiled with 15, 20 and finally 23 different types (Baur et al., 1944; Baur, 1947, 1948). Baur's work was later continued by P. Hess and H. Brezowsky, resulting in 1952 in a new calendar of *Grosswetterlagen* for Europe (Hess & Brezowsky, 1952), and in 1969 with a fully revised classification in which 29 *Grosswetterlagen* are distinguished (Hess & Brezowsky, 1969). The latest version of the calendar contains the *Grosswetterlagen* over the period 1881-1976 (Hess & Brezowsky, 1977).

Fliri (1974) investigated the relation between typical *Grosswetterlagen* and the distribution of precipitation and temperature in the Alpine region, using the classification of Hess and Brezowsky (1969) who provided the only available calendar for the period 1931-1960.

Baur's system, which was especially adapted to the continent of Europe with Germany as the centre, appeared to be less suitable for the border areas than was originally expected. Application of this system did not lead to satisfactory results, especially in the Alpine region which is on the one hand exposed to orographic influences and on the other to the influence of the Mediterranean. On this ground Lauscher (1954) came to the conclusion that a modification of Baur's system was necessary, at least for the eastern Alps. Apart from Baur's main types "high- and low pressure situations" with three subdivisions each, Lauscher's system distinguishes three more types viz. "fringe anticyclonic-", "indifferent-" and "fringe cyclonic situations" in which for each main type eight flow directions are distinguished. Contrary to Baur, Lauscher aimed mainly at the distribution of the height of the 1000 mb level (see also Lauscher, 1958).

On the basis of Lauscher's division, Fliri (1962b) investigated the climate of Tyrol (Austria) according to the method of dynamic climatology. In his extensive study the relations between meteorological parameters such as precipitation and temperature and the effective large-scale weather types *(Grosswitterungslagen)*, based on a period of 10 years, are presented and elucidated. Fliri concludes that the properties of the various large-scale weather types are rather stable as far as their effect on the local weather is concerned.

For the Swiss Alpine region Schüepp (1957) suggested a new classification of weather situations *(Wetterlagen)*. He is of opinion that a division on the basis of a region as large as Europe, as in Baur's system, is not satisfactory to characterize the weather situation of an Alpine area where orographic phenomena have a regional impact on the weather. In order to characterize weather conditions he derived a classification based on a division of

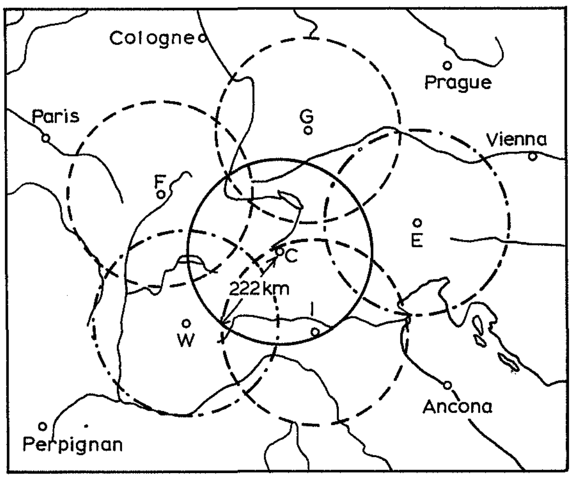


Fig. 2.1 *Regional division of the Alps and surroundings used by Schüepp in his classification of Wetter- and Witterungslagen (Weather-situations and Weather-types). The co-ordinates of the respective centres of the sub-areas are:*

Central Alpine area	C	*46.50° N*	*9.00° E*
Western Alpine area	W	*45.00° N*	*6.50° E*
Eastern Alpine area	E	*47.00° N*	*13.00° E*
Eastern part of France	F	*47.75° N*	*5.75° E*
Southern Germany	G	*49.00° N*	*10.00° E*
Northern Italy	I	*44.75° N*	*10.00° E*

(After Schüepp, 1957)

the Alps in regions with a radius of two degrees of latitude, i.e. 222 km (fig. 2.1), in opposition to the system of Hess and Brezowsky, which considered a large-scale classification for a whole continent. Schüepp no longer speaks about LARGE-SCALE WEATHER SITUATIONS *(Grosswetterlagen)* but instead of REGIONAL WEATHER SITUATIONS *(Wetterlagen)* and REGIONAL WEATHER TYPES *(Witterungslagen)*. He defines a *Wetterlage* as the momentary situation of the weather of no longer than 24 hours duration, and a *Witterungslage* as the characteristic development of the weather during a period of several days. Both the flow at the 500 mb level, being the basis of Baur's system, and the flow at the 1000 mb level, being the basis of Lauscher's system, are used as the framework for the new classification of *Wetterlagen*. This combination with eleven types on each level, leads to a total of 121 *Wetterlagen* (Schüepp, 1957).

Two years later, Schüepp (1959b) published a method for the classification of *Witterungslagen*. This classification is based on Lauscher's classification with the extension of Lauscher's scheme from 5 to 6 classes and from 17 to 33 types.

The basis for a completely revised classification system of both *Wetterlagen* and *Witterungslagen* was published in 1966 (Schüepp and Fliri, 1966), and a calendar for the period 1955-1967 was published in 1968 (Schüepp, 1968). The system is now routinely used by the Swiss Meteorological Institute, and a calendar is published every year in the "Annalen der Schweizerischen Meteorologischen Zentralanstalt".

Gressel (1954, 1959) also considered the problems of developing a classification system of weather types for the Alpine region. In his approach emphasis is laid on the displacement of steering centres as opposed to the more static aspects of the *(Gross)Wetterlage* approach. Gressel critisized Schüepp's system in that it did not provide a perspective to the evolution of the weather processes.

Lamb (1950, 1964) has developed a scheme for describing surface air flow types for the British Isles based on earlier work by Levick (1949, 1950). Eight directions of flow are distinguished, referring to the general air flow over the British Isles and to the overall movement of synoptic systems, and three non directional types are also introduced. A revised classification has more recently been published (Lamb, 1972).

Other classifications, proposed by Cadez (1957) and Mertz (1957), based on the direction of air flow in the lower troposphere and at the 500 mb level together with anticyclonic and cyclonic patterns, have not been applied beyond the period of investigation and are of no further interest here since a calendar is not available.

Several synoptic classifications dealing with the relationships of surface- and upper air flow and pressure distributions have been developed. Of these the work of Gazzola and Montalto (1960) should be mentioned. They used eleven patterns at the 1000 mb and 500 mb level in a study of winter precipitation in Italy.

Kirchhofer (1976) investigated the relationship between small-scale weather phenomena and synoptic scale circulation patterns as described earlier (Kirchhofer, 1974), for the period 1961-1970. He correlated 500 mb patterns with several meteorological variables and classified synoptic weather situations for a selected group of stations.

An objective classification of daily 500 mb patterns over Europe has been performed by Kruizinga (1978) based on principal components and cluster analysis. The use of principal components was earlier proposed by Kuipers (1970).

3 SELECTION OF A CLASSIFICATION SYSTEM FOR THE CURRENT STUDY

3.1 Criteria for Selection

To start an investigation on the hydrological behaviour of the Alpine discharge area of the river Ahr in relation to (large-scale) weather types raises the question of which existing classification system should be applied. It is difficult to make an objective evaluation of the merits of the different classification systems, because this depends to a large extent on the objectives of the classifications, the investigation to which the classifications are applied, and the area of investigation with respect to the position of the described weather systems.

The most objective criterion to decide upon the usefulness for hydrological purposes seems to be the degree of association between the distinguished weather types and hydrologically relevant meteorological parameters such as temperature, precipitation and cloudiness. It is to be expected that the obtainable degree of association is related to the degree of detail in the classification system. This proceeds from the fact that the highest degree of detail offers the best possibilities for subsequently grouping together certain types, adapted to use and specific application.

3.2 Comparison of Systems

The variety of classification systems mentioned for the European continent and especially for the Alps has enabled climatologists to compare the effectiveness of the different systems. Table 2.1 gives an overview of the existing classification systems especially developed for the Alpine region and the European continent. Several investigators have studied the relations between meteorological parameters in a certain region on the one hand and weather types from several classifications on the other, with the results used to evaluate the systems. Schüepp's (1968) system, which is a combined version of his classification of *Wetterlagen* (Schüepp, 1957) and *Witterungslagen* (Schüepp, 1959b), has not been subjected to a comparison.

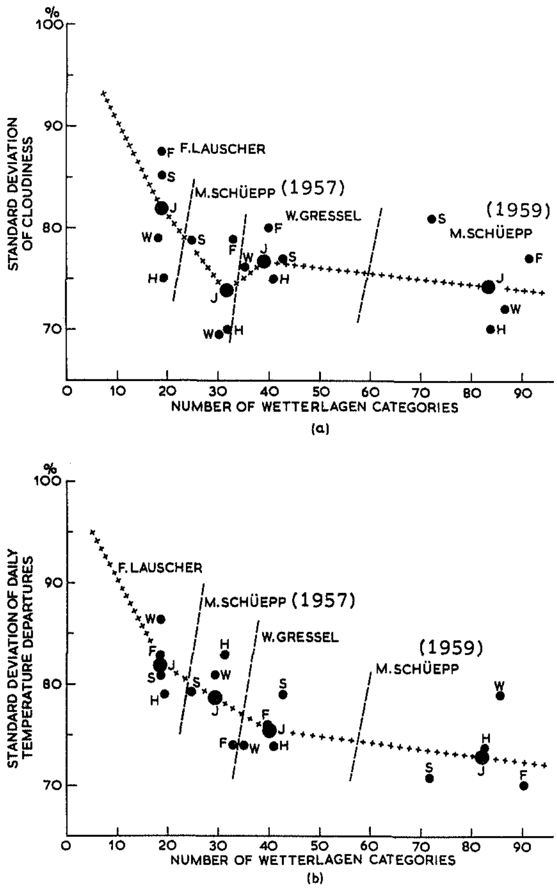
Lauscher (1954, 1963) stated on theoretical grounds that the *Grosswetterlagen-system* of Hess and Brezowsky is not satisfactory for the Alpine region,

Table 2.1 Synoptic classifications developed for the European continent (Baur/Hess-Brezowsky) and for the Alps.

Reference	Area	Basis	Number of types	Catalogue period
Hess/Brezowsky (1977)	Europe	500 mb flow	29	1881-. ..
Cadez (1957)	Ljubljana	surface flow	7	1942-1947
Mertz (1957)	Alps	500 mb flow	19	1950-1952
Lauscher (1958)	Eastern Alps	surface flow	22	1946-. ..
Gressel (1959)	Alps	movement of steering centres		1946-....
Schüepp (1957)	Alps	Wetterlagen 500/1000 mb flow	121	
Schüepp (1959)	Alps	Witterungslagen surface flow	33	
Schüepp (1968)	Alps	Wetter- and Witterungslagen 500/1000 mb flow	360	1953-. ..

not even for the Bavarian Alps, because of the Mediterranean influences, especially important in the southern Alps.

Grunow (1964b) analysed sunshine records of Hohenpeissenberg (Bavaria) in relation to the weather types according to the systems of Hess-Brezowsky (1952), Lauscher (1958), Gressel (1959) and Schüepp (1957 & 1959b), and determined the probability of sunshine and its reliability for each weather type. He concluded that Schüepp's 33-type classification (1957) was the most satisfactory and produced the highest reliability.



Fliri (1964a) independently came to the same conclusion, based on a comparitive investigation using the degree of cloudiness and temperature in the locations Säntis (Switzerland) and Sonnblick (Austria), for the period 1955-1963. Fig. 2.2 shows the standard deviations for each classification system as a percentage of the overall standard deviation of the climatological series for both parameters. The largest variability occurs with Lauscher's system which has the least categories. The smallest variability occurs with Schüepp's 121-type *Wetterlage-classification*, which offers by far the greatest diversity with eleven types of flow on both the 500 mb and the 1000 mb levels.

Fig. 2.2 The standard deviation of (a) cloudiness and (b) temperature departures for different classification systems for the Alps, in each season and for the annual mean, as a percentage of the standard deviation for the 1955-1963 series. W=winter, S=summer, F=spring, H=autumn, J=annual mean (from Fliri, 1964a)

Another important aspect to be considered, however, is the mean duration of the distinguished weather types. Fliri (1964a) computed that the mean duration for the period 1955-1963 is only 1.2 days for the Schüepp 121-type scheme, 1.4 days for Gressel's scheme, 1.7 days for Lauscher's scheme and 4.6 days for Schüepp's 33-type *Witterungslagen* scheme. Despite the fact that Schüepp's system is based on a regionally restricted area, it describes weather types with a mean duration of several days. The combination of high mean duration and low standard deviations of meteorological parameters is of importance for the study of hydrologic phenomena in relation to weather types.

A final point which has not yet been taken into account is the availability of a calendar and the period which is covered. In table 2.1 the period is indicated for which a catalogue of the different classification systems is available. Despite the fact that a catalogue of Schüepp's (1968) revised system has existed since only 1953, it has been chosen for further investigations because:

a) It shows by far the highest degree of detail and offers the best possibilities for subsequent regrouping.
b) It combines a high mean duration of weather types (4-5 days) with a relatively high association to meteorological parameters such as sunshine and temperature.
c) Hess-Brezowsky's system appears to be less appropriate for the Alpine region (Lauscher, 1954, 1963).
d) Lauscher's and Gressel's systems, with a mean duration of 1.7 and 1.4 days respectively, can hardly be regarded as **WEATHER TYPES** *(Witterungslagen)* in the strict sense of the word, i.e., covering a period of several days.

3.3 Schüepp's Classification System

Schüepp's classification system of WEATHER SITUATIONS and WEATHER TYPES relates to a regionally small scale in comparison with the system of Hess and Brezowsky, which considers LARGE-SCALE WEATHER TYPES. The system has been designed in such a way that it is generally applicable, i.e., for any region. For application to the Alpine region, a division of the Alps into six subareas is proposed with a radius of two degrees of latitude (222 km) as shown in fig. 2.1.

Only for the central Alpine area, with its centre in the Rheinwald-area (fig. 2.3) a calendar of WEATHER SITUATIONS and WEATHER TYPES has been compiled by the "Schweizerische Meteorologische Zentralanstalt" in Zurich (Switzerland). The study area (the Ahr valley) is situated near the eastern border of this circle, and so is quite peripheral.

At the start of this investigation the calendar was available from 1953, but will be completed back in time until 1935 (Schüepp, 1968), the year when a start was made with the construction of 500 mb maps.

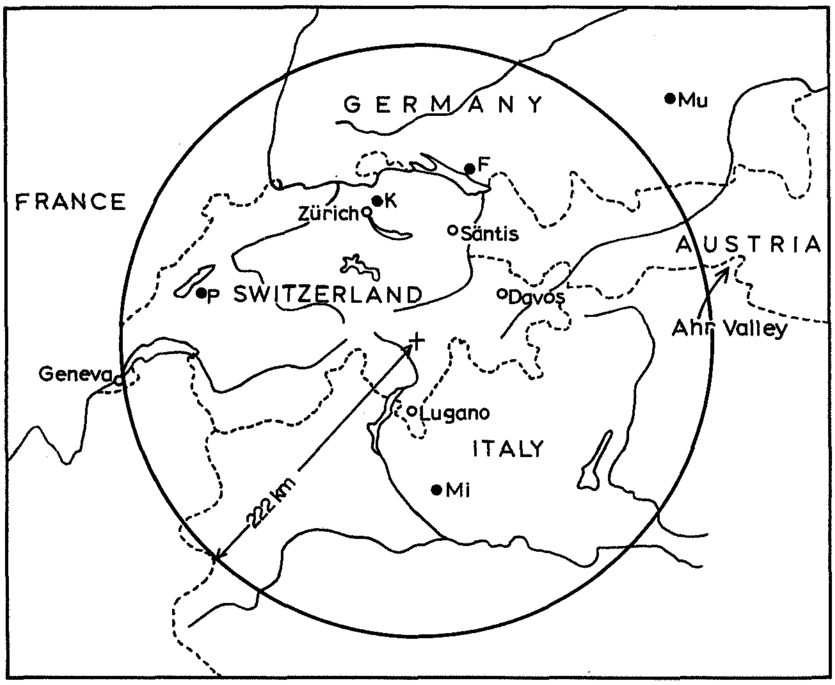


Fig. 2.3 Circumsription of the central Alpine area according to Schüepp's classification of weather situations. The co-ordinates of the central point are 46.50° N / 9.00° E.

Stations of the observation-network for the classification are:

F = *Friedrichshafen*　　Mu = *Munich (northern side of the Alps)*
K = *Kloten-Flughafen*　　Mi = *Milan (southern side of the Alps)*
P = *Payerne*

(After Kirchhofer, 1971)

System Parameters

In classifying both weather types and weather situations, Schüepp aimed at a description of the weather conditions which was as complete and objective as possible, but which led to a very large number of parameters. The advantage of such a system is that one can select relevant parameters to define distinct weather types adapted to a specific type of investigation. For a complete description of Schüepp's calendar the reader is referred to the literature (Schüepp, 1968). In the present study only the most important parameters which have been chosen as the basic elements for a "WEATHER TYPE HYDROLOGICAL" classification will be discussed.

Surface-level flow (D)

The direction of surface-level flow is extracted from the barometric pressure map reduced to sea-level. Instead of the gradient wind, the geostrophic wind is used to approximate the actual direction of flow. Wind directions are classified into eight sectors of 45 degrees, namely: NE, E, SE, S, SW, W, NW and N.

In the case of a flat pressure distribution at sea level, the direction of the wind at the 500 mb level is given instead of the surface flow direction. If also at the 500 mb level pressure differences are weak, the situation is described as a flat pressure situation (F).

If no uniform flow exists at sea level, i.e., flow does not occur from a well defined direction, the following cases are distinguished:

(L) Low pressure cell
(X) Saddle
(H) High pressure cell

Upper-level flow (d)

The direction of upper-level flow is compiled from wind directions at the 500 mb level in Payerne, Munich and Milan (fig. 2.3) as an average for the region. The 500 mb level is far beyond the mountain crests and consequently the actual wind at this level will not deviate much from the geostrophic wind.

Distinction between surface-level flow and upper-level flow **(B)**

By means of a parameter (B), which denotes the *baroclinicity* distinction between flow circumstances at sea level and those at the 500 mb level is indicated by the following cases:

Baroclinicity

Code	Description
0	Weak winds at both levels
1	Same wind direction at both levels
2	Upper wind shifted left with respect to surface wind
3	Upper wind shifted right with respect to surface wind
4	Opposite directions between both levels
5	Pressure gradients only at sea level (upper-level flow weak)
6	Pressure gradients only at 500 mb level (surface-level flow weak)
7	Low pressure cell crossing the region
8	Saddle crossing the region
9	High pressure cell crossing the region

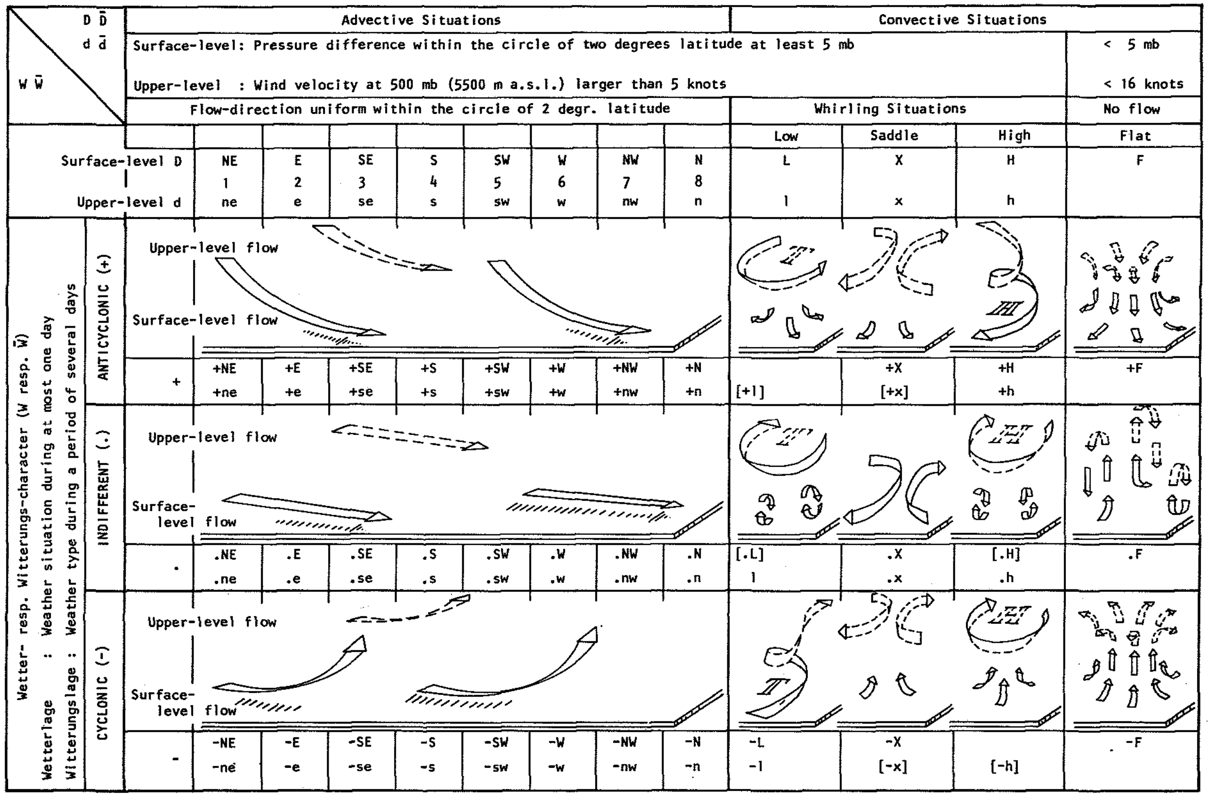
Weather situations with baroclinicity 7 up to 9 refer to the 500 mb level in case uniform flow exists at the surface level.

Cyclonicity **(C)**

In order to describe the character of the general circulation above the Alps data on precipitation and mean duration of sunshine are applied as a mean of nine stations spread over the area. A high duration of sunshine in combination with the absence of precipitation is related to sinking air, while extended areas of precipitation are related to rising air. Three classes are distinguished: *anticyclonic, indifferent and cyclonic.*

3.4 Selection of Weather Types

Schüepp's classification is compiled in such a way that nearly any weather situation can be described in an objective way by means of a variety of parameters. The main advantage of this classification is that on the basis of these parameters a selection of distinct weather types can be performed, adapted to the specific investigation. The choice of parameters is explained as follows and arguments produced in support of a division into main weather types.



Scheme 2.2 Scheme of Wetter- and Witterungslagen (weather situations and weather types), based on cyclonicity (C), *surface-level flow* (D) *and upper-level flow (500 mb-level)*(d) *(Translated from Schüepp, 1968)*

On the basis of 12 flow conditions at the surface level (D), and the cyclonicity (C) with three classes, viz. anticyclonic (+), indifferent (·) and cyclonic (-), 36 circulation types can be distinguished which form the framework of the classification of *Wetter*- and *Witterungslagen*. Introduction of a comparison of the flow conditions at the surface level (D) with those at the 500 mb level (d), expressed in 10 classes of baroclinicity (B), brings the total number of types to 360. A graphical presentation is given in scheme 2.2, in which bold type arrows represent surface flow and broken-line arrows the upper-level flow.

In theory, all combinations of surface flow (D = NE up to N, L, X, H and F) and baroclinicity (B = 0 up to 9) may occur, but it appeared that certain combinations are rare or do not occur al all. In fig. 2.4 it is shown that only 80 (or 22%) of the 360 theoretical situations occurred on 95% of the days in the period 1953-1975, and that in this period 160 different situations actually occurred in all.

The Significance of Baroclinicity

To investigate the relation between hydrological phenomena and weather situations the precondition must be made that the total collective can be split

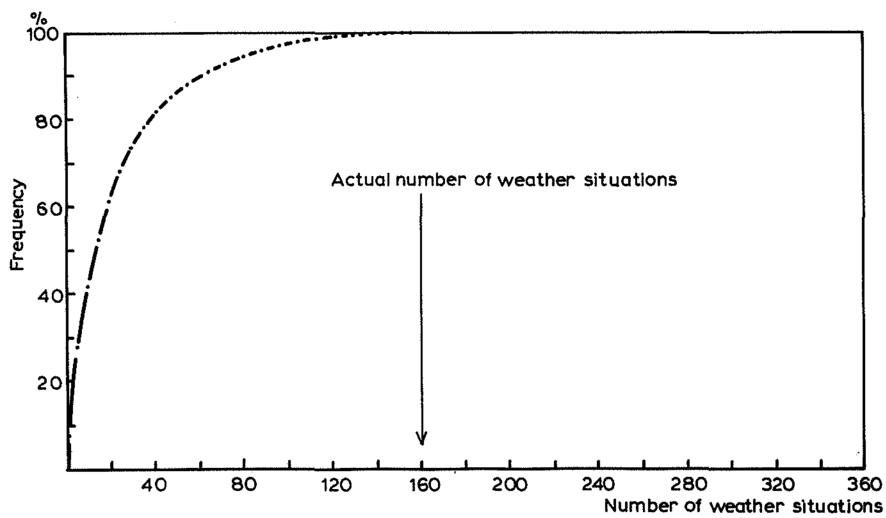
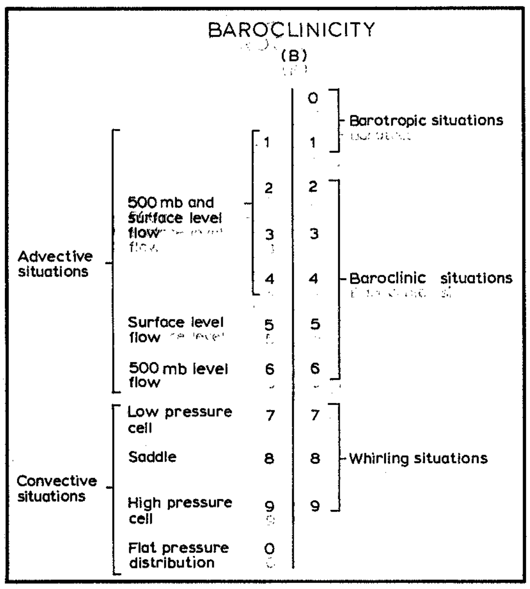


Fig. 2.4 Cumulative distribution of occurrences of weather situations, as a percentage of the total number of days (1953-1975), plotted against the number of different weather situations. From 360 theoretical situations only 160 actually occurred during this 23-years period

into a restricted number of distinct classes in order not to result in populations too small for each class. Since baroclinicity, with 10 distinct cases, extends the range of types from 36 to 360, it is appropriate to consider how far this distinction in baroclinicity is hydrologically relevant.

On the basis of baroclinicity the total collective can be divided in two ways, i.e., (1) with emphasis on flow conditions in relation to the temperature structure of the atmosphere, and, (2) with emphasis on advection and convection (air masses) (scheme 2.3).



Scheme 2.3 Division of weather situations by means of the baroclinicity parameter in (1) barotropic-, baroclinic- and whirling situations, and, (2) in advective and convective situations (For explanation see text)

Starting with the first, the change in direction and speed of the flow at the surface and 500 mb levels, as indicated by means of baroclinicity 0 up to 6, is directly related to the temperature structure of the atmosphere between the surface and 500 mb levels. Two groups can be distinguished, i.e., B = 0 and B = 1 both referring to a BAROTROPIC atmosphere and B = 2 up to 6, referring to a BAROCLINIC atmosphere. The significance of this baroclinicity mainly lies in the development of the weather, in the sense that a shift of the wind to the right at higher levels (B = 3) is related to the advection of warmer air into the region and a shift to the left (B = 2) with the advection of colder air. The distinction in baroclinicity, especially B = 2, 3 and 4, is therefore significant for the development in the next few days, rather than for the momentary situation.

If we focus on the second point (air masses), a distinction can be made between ADVECTIVE and CONVECTIVE situations. ADVECTIVE situations (B = 1 up to 6), see scheme 2.3 and fig. 2.5, are characterized by advection of air mass-

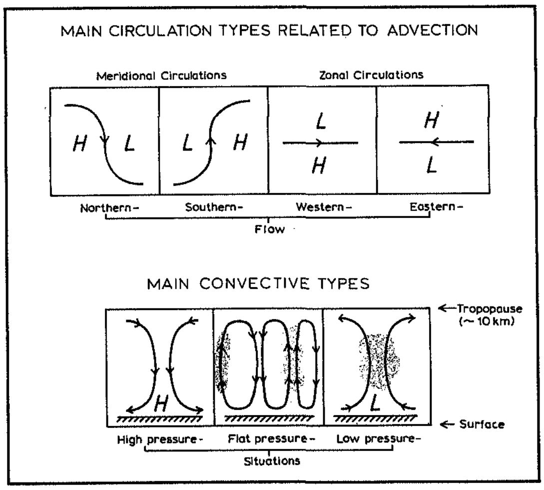


Fig. 2.5 Main circulations based on a distinction between advection (a) and convection (b), related to pressure distribution

(a) Schematic pressure distributions related to mainly horizontal flow (advection)

(b) Schematic view of convective types, during which vertical air movement is of crucial importance for local weather conditions

es from beyond the Alpine region under mainly horizontal flow conditions, while CONVECTIVE situations (B = 0, 7 up to 9) are characterized mainly by vertical movements or by the lack of uniform flow.

Within the group of advective types, upper-level flow (B = 6) is distinguishable from the other advective types which are characterized by the existence of uniform flow at least at the surface level. Also, from a genetic point of view, upper-level flow forms a distinct circulation type which is plausible from its characteristic frequency distribution of flow directions, mainly from SW, W and NW (Kirchhofer, 1971). Lauscher (1954, pg. 147) also demonstrated the specific character of upper-level flow as a typical West-circulation *(Westwetterlage)*. In less elevated areas, the combination of uniform flow at the 500 mb level and slight pressure gradients at the surface level could be regarded as a convective type, in so far as surface flow conditions are concerned, but for the Alps with elevated crests at about 3000 meter a.s.l., advection at the 500 mb level will undoubtedly influence the air mass exchange in the higher valleys. Therefore, upper-level flow will not be regarded as a distinct group of advective circulations.

The situations with baroclinicity 7 to 9 refer to the 500 mb level in case uniform flow exists at the surface level. Since in these cases there is advection of air at the surface level and, in addition, since the cyclonic, indifferent or anticyclonic character is expressed by the cyclonicity parameter (C) these situations will be more or less comparable with the other advective types and will be taken together.

Major Groups of Circulation Types	Matrix of 36 Major Circulation Types			
	Flow Direction (D,d)	Cycloni-city (C)	Individual Circulation Types	
			Type	Identifica-tion
Advection at surface-level (D) or/and at 500 mb-level (d)	NE up to N (ne up to n)		Anticycl. NE, etc.	+NE,..., +N
	..		Indifferent NE, etc.	·NE,.. , ·N
			Cyclonic NE, etc.	-NE,..., -N
Whirling Situations	H,h (high)		Stable high	+H
	...		High at 500 mb, Indiff. at surface	·H
			High at 500 mb, Cyclonic at surface	-H
	X,x (saddle)		Anticycl. saddle	+X
	..		Indifferent saddle	·X
			Cyclonic saddle	-X
	L,l (low)		Low at 500 mb, High at surface	+L
	..		Low at 500 mb, Indiff. at surface	
			Low at 500 mb Low at surface	-L
Flat Pressure Distributions	F,f (flat)		Anticycl. flat	+F
	..		Indifferent flat	·F
	,,	-	Cyclonic flat	-F

Scheme 2.4 Circulation types based on surface-level flow (D), *500 mb-level flow* (d) *and cyclonicity* (C)

The situation with baroclinicity (B = 0), indicates that both at the surface and at the 500 mb level only slight pressure gradients exist. It is found that situations F and f, i.e., a flat pressure distribution at either the surface or 500 mb levels respectively, occur almost uniquely in combination with B = 0. Therefore, the situations F, f or B = 0 are combined in one group, i.e., flat pressure distributions (F).

According to these considerations, a total of 36 weather types are distinguished, of which 24 are advective types, 9 whirling types and 3 flat pressure types (see scheme 2.4).

4 HYDROLOGICALLY RELEVANT CLASSES OF WEATHER TYPES

4.1 Introduction

The classification of circulation types applied in the investigation is primarily directed towards the relation between discharge-hydrological phenomena and circulation types.

Discharge from Alpine drainage basins which are partly covered by glaciers and during a considerable part of the year with snow, is governed by runoff from snow- and glacier-melt on the one hand and by runoff from precipitation on the other. As previously discussed in chapter I, the melting process is governed by a variety of meteorological and physical parameters, of which incoming and reflected short-wave radiation, condensation at the snow surface and heat input from advection are the most important. However, such data are not available from the study area, so the investigation is necessarily based on precipitation and temperature data - the only data available. However, several investigators such as Martinec (1960, 1965, 1970), Lang (1967), Herrmann (1974) and several others reported by Gray (1973) have produced surprisingly good results using the degree-day-method, based on a correlation between the number of degree-days and the measured daily snow-melt (Linsley et al., 1949). Both temperature and precipitation, therefore, are regarded as the basic meteorological parameters that characterize circulation types with respect to their influence on hydrology, and will be used to form hydrologically relevant classes of weather types.

4.2 Premises for a Reduction of Weather Types

In order to investigate the relation between circulation types and hydrologic phenomena, it is necessary to reduce the total of 36 weather types to a restricted number of classes, which are more or less homogeneous with respect to their influence on hydrology. Two ideas have led to such a reduction.

In the first place, it seems obvious to use temperature and precipitation as basic criteria to decide whether or not certain circulation types can be joined to form homogeneous groups with respect to their influence on hydrology. By doing this, it is necessary, as far as temperature is concerned to split the observations on at least a seasonal basis to account for broad seasonal influences. This may result in a **seasonally dependent classification** of weather types, which means that the classes selected will not necessarily comprise the same circulation types for each season.

Secondly, from a meteorological point of view it is possible to select classes of circulation types, for example on the basis of flow direction, advective and convective types and source areas of air masses, which consist of the same circulation types throughout the year. These groups are consequently likely to be less homogeneous with respect to their influence on hydrology in terms of temperature and precipitation characteristics.

The character of the weather, including temperature and precipitation phenomena, may show large regional differences within one particular circulation type especially in the Alpine mountain region. These are most clearly illustrated by the climatic differences between the northern and the southern side of the Alps (Fliri, 1975). This means that the first approach has predominantly local meaning if applied on the basis of local temperature and precipitation data. Against a potential lack of regional meaning however, a better correlation might be obtained between circulation types and hydrological phenomena.

In fact both aspects should be incorporated in order to decide upon a reduction of weather types. Therefore, the combination of temperature and precipitation characteristics on the one hand and air mass advection in relation to source areas on the other has been investigated to form the basis for a reduction of weather types.

4.3 Weather Types and Temperature

Because of the large amplitude of the annual mean temperature cycle (fig.2.6) it is impossible to use actual temperature data to compare circulation types with each other, unless a division of the year into shorter periods is performed. Such a division, for example on a monthly basis, would lead to an

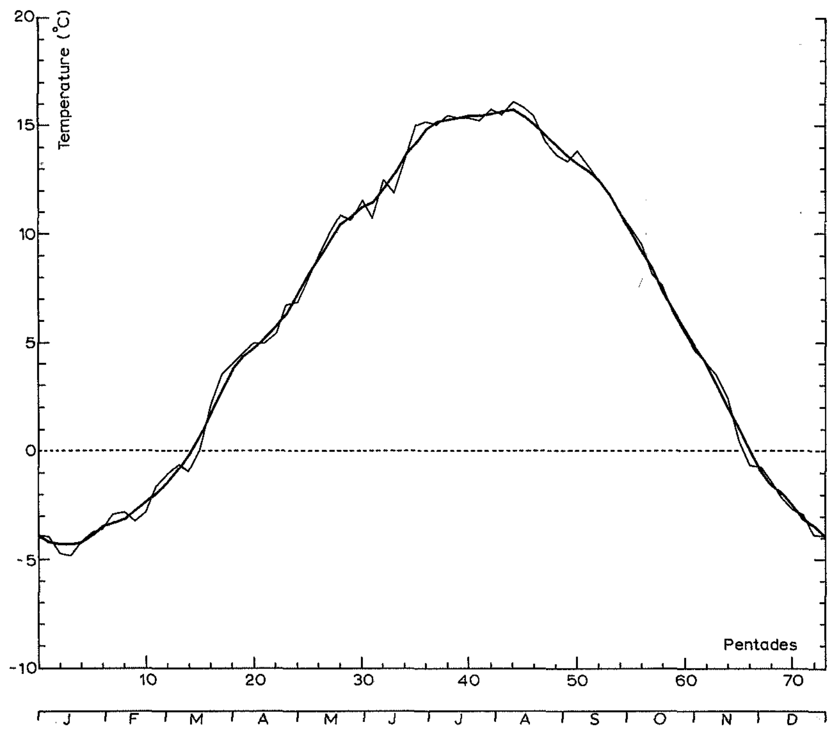


Fig. 2.6 Annual Cycle of Temperature at Antholz computed from mean pentad (5 days) values (thin line) and from the running mean over 5 pentads (thick line) for the period 1953-1975

undesirable reduction of the number of elements within each group. A transformation of temperatures has thus been performed.

Instead of actual temperature, departures from the mean annual cycle have been used, so that seasonal influences, which bring about the annual cycle and which are themselves independent of the circulation types are eliminated, and the number of elements within each circulation type is kept as large as possible.

An essential disadvantage occurs when certain types are preferentially accorded with specific seasons, and if their influence on the mean annual cycle changes from one season to another. This problem is partly alleviated by dividing the year on a seasonal basis.

The following meteorological seasons are used:

Winter :	December, January, February
Spring :	March, April, May
Summer :	June, July, August
Autumn :	September, October, November

The temperature data used are from the station Antholz (1236 m), situated about 20 km south-east of St.Jakob in the valley of Antholz (fig. 1.1), since the data from St.Jakob and Rain in Taufers are both interrupted by several years of non-observation.

For computation of the mean annual temperature cycle, use is made of pentads, i.e., 5-days periods. Each year is divided into 73 pentads. For each pentad, mean daily temperatures (i.e., the mean of daily maximum and daily minimum) for all 23 years are added and divided by the number of days (23 * 5 = 115). The pentade mean for the i^{th} pentad (τ_i), is computed according to:

$$\tau_i = \frac{1}{115} \sum_{j=1}^{23} \sum_{k=i*5}^{i*5+5} t_{j,k}$$

with $t_{j,k}$ = daily mean temperature of the k^{th} day and j^{th} year

i = pentad number

The cycle of mean temperature per pentad is presented in fig. 2.6 for the period 1953-1975 at the station Antholz. The fluctuations have been smoothened by taking for each pentad (i) the running mean (τ'_i) over 5 pentads according to:

$$\tau'_i = \frac{1}{5} \sum_{l=i-2}^{i+2} \tau_l \quad (i > 2)$$

and results in the so-called "normal cycle" of temperature as shown in fig. 2.6. For each day, the temperature departure from this "normal cycle" (ΔT) is computed, and results in a population which is as large as possible for each season and for each circulation type.

All temperature departures for each weather type are regarded as samples with a mean and standard deviation (tables 2.2, a to d) and are used to compare the influence of the individual types on temperature.

Table 2.2[a] The number of days and temperature and precipitation characteristics in the Ahr valley for different weather types, based on the period 1953-1975.

$\overline{\Delta T}$ = Mean temperature departure from normal pentad values;
$s_{\Delta T}$ = Standard deviation of ΔT;

WINTER

	Weather Type	Number of days	Temperature $\overline{\Delta T}$ (°C)	$s_{\Delta T}$	Percentage of days with P>1 mm	P>10 mm	P>20 mm	Mean precipitation per weather-type day (mm)
ANTICYCLONIC	+NE	78	-0.9	3.3	1%			0.0
	+E	222	-1.7	4.1	-			0.0
	+SE	24	-1.9	2.4	-			0.0
	+S	19	-0.7	3.5	5%			0.1
	+SW	18	+0.5	4.7	6%			0.1
	+W	49	-0.1	3.9	4%			0.1
	+NW	38	+1.2	3.4	3%			0.1
	+N	25	+0.4	3.7	4%			0.3
		473						
INDIFFERENT	.NE	81	-1.6	5.8	16%	4%	1%	1.0
	.E	137	-2.7	3.7	4%	1%	-	0.3
	.SE	61	+0.1	4.3	8%	-	-	0.3
	.S	71	+1.3	2.9	15%	18%	1%	0.9
	.SW	102	+2.7	2.7	20%	2%	1%	1.1
	.W	124	-0.2	3.4	19%	4%	-	1.1
	.NW	90	-0.0	4.4	12%	2%	-	0.7
	.N	28	-2.0	4.4	4%	4%		0.5
		694						
CYCLONIC	-NE	23	-1.4	3.4	22%	9%	9%	2.6
	-E	29	+0.3	4.7	31%	3%	-	1.4
	-SE	17	-1.2	4.5	41%	12%		2.8
	-S	44	+1.6	3.4	43%	11%	-	2.8
	-SW	99	+2.2	2.5	53%	23%	6%	5.5
	-W	190	+0.7	3.3	39%	16%	3%	3.4
	-NW	130	-0.1	3.8	45%	22%	8%	5.3
	-N	17	+0.8	2.9	24%	6%	-	1.3
		549						
WHIRLING SITUATIONS — *High*	+H	41	+0.3	3.8	2%			0.1
	.H	10	+2.0	1.0	-			0.0
	-H	-	-	-				-
		51						
Saddle	+X	3	-5.6	1.7				0.0
	.X	3	+4.9	0.3				-
	-X	-	-	-				
		6						
Low	+L	3	-2.8	4.5	-	-		0.0
	.L	26	-0.6	3.6	19%	4%	-	1.0
	-L	91	+0.5	3.1	35%	7%	1%	2.3
		120						
Flat	+F	81	+0.3	3.4	16%	5%	1%	1.1
	.F	46	-1.4	4.1	9%	-	-	0.3
	-F	11	+2.0	1.7	18%			0.9
		138						
	Total	2031						

Table 2.2[b] The number of days and temperature and precipitation characteristics in the Ahr valley for different weather types, based on the period 1953-1975.

$\overline{\Delta T}$ = Mean temperature departure from normal pentad values;
$s_{\Delta T}$ = Standard deviation of ΔT;

SPRING

		Weather Type	Number of days	Temperature $\overline{\Delta T}$ (°C)	$s_{\Delta T}$	Percentage of days with P>1 mm	P>10 mm	P>20 mm	Mean precipitation per weather-type day (mm)
ANTICYCLONIC		+NE	70	+0.5	2.8	4%	1%		0.5
		+E	88	-1.6	3.7	5%	-		0.1
		+SE	14	+0.9	5.3	-			0.0
		+S	16	+1.5	3.6	6%	-		0.2
		+SW	13	+1.0	3.7	23%	8%		1.6
		+W	37	+3.3	3.5	5%	3%		0.6
		+NW	55	+0.3	3.0	7%	-		0.3
		+N	29	+0.5	2.8	3%			0.1
			322						
INDIFFERENT		.NE	145	-2.1	3.6	17%	3%	1%	0.9
		.E	132	-1.5	3.9	12%	-	-	0.4
		.SE	35	+1.1	2.6	20%	6%	-	0.5
		.S	62	+1.3	2.9	19%	3%	2%	1.2
		.SW	115	+1.8	2.7	26%	3%	-	1.2
		.W	165	+0.8	3.4	29%	7%	2%	2.1
		.NW	51	-0.9	3.4	24%	4%	2%	1.5
		.N	55	-2.1	3.5	18%	4%	-	1.2
			760						
CYCLONIC		-NE	77	-1.3	2.9	38%	6%	1%	2.2
		-E	41	-1.8	3.1	24%	5%	2%	2.1
		-SE	14	+0.8	2.3	43%	-	-	1.7
		-S	43	+1.2	2.5	42%	21%	5%	2.9
		-SW	146	+0.5	2.8	62%	18%	3%	4.9
		-W	119	-0.1	3.2	50%	8%	2%	3.2
		-NW	49	-1.2	3.4	31%	8%	6%	10.3
		-N	35	-3.8	3.7	37%	3%	-	1.8
			524						
WHIRLING SITUATIONS	*High*	+H	32	+2.3	2.3				0.0
		.H	4	+1.7	4.3				0.1
		-H	-	-	-				-
			36						
	Saddle	+X							
		.X	-	-	-	-			-
		-X	3	+2.5	1.2	33%			0.6
			3						
	Low	+L	3	+4.4	0.6	-	-		0.0
		.L	36	+0.5	3.0	25%	3%	-	1.3
		-L	150	-2.3	2.9	46%	13%	5%	4.4
			189						
	Flat	+F	133	+1.1	3.4	11%	3%		0.0
		.F	81	+1.4	1.9	23%	2%		1.0
		-F	32	+1.1	2.1	31%	16%		2.9
			236						
		Total	2070						

Table 2.2[c] The number of days and temperature and precipitation characteristics in the Ahr valley for different weather types, based on the period 1953-1975.

$\overline{\Delta T}$ = Mean temperature departure from normal pentad values;
$s_{\Delta T}$ = Standard deviation of ΔT;

SUMMER

		Weather Type	Number of days	Temperature $\overline{\Delta T}$ (°C)	$s_{\Delta T}$	Percentage of days with P>1 mm	P>10 mm	P>20 mm	Mean precipitation per weather-type day (mm)
ANTICYCLONIC		+NE	33	+0.3	2.8	25%	6%		1.5
		+E	54	-1.1	3.7	15%	2%		0.8
		+SE	-	-	-	-	-		-
		+S	4	+4.7	1.8	-	-		0.0
		+SW	18	+2.9	2.1	11%	6%	-	1.4
		+W	118	+2.3	2.7	19%	5%	3%	1.4
		+NW	63	+0.7	3.1	8%	2%	-	0.4
		+N	60	+0.3	2.6	15%	2%		0.7
			350						
INDIFFERENT		.NE	129	-2.2	3.0	43%	9%	1%	2.5
		.E	94	-1.0	2.9	34%	10%	1%	2.6
		.SE	-	-	-	-	-	-	-
		.S	-	-	-	-	-		-
		.SW	89	+1.9	2.9	46%	15%	-	3.8
		.W	217	+0.4	2.9	47%	12%	1%	3.7
		.NW	71	-0.6	1.8	35%	7%	11%	2.0
		.N	27	-1.8	2.7	41%	4%	-	1.7
			627						
CYCLONIC		-NE	111	-2.4	3.6	57%	22%	5%	5.0
		-E	35	-2.2	3.5	63%	29%	14%	7.3
		-SE	-	-	-	-	-	-	-
		-S	6	-0.8	1.8	50%	50%	33%	7.7
		-SW	127	+0.2	3.0	70%	23%	5%	6.0
		-W	184	-0.9	2.8	70%	28%	11%	7.6
		-NW	30	-2.0	3.2	60%	23%	3%	5.4
		-N	9	-1.8	2.8	33%	11%	-	2.9
			502						
WHIRLING SITUATIONS	*High*	+H	39	+1.3	3.3	8%	-	-	0.4
		.H	5	+0.2	2.1	20%	20%	20%	4.8
		-H	-	-	-	-	-	-	-
			44						
	Saddle	+X							
		.X							
		-X							
	Low	+L	5	+4.1	1.6	40%	20%	-	3.7
		.L	37	+0.7	2.6	38%	8%	3%	2.6
		-L	149	-1.9	3.2	66%	25%	10%	7.9
			191						
	Flat	+F	123	+2.4	2.6	12%	3%	1%	1.0
		.F	192	+1.5	2.2	47%	5%	1%	2.1
		-F	86	+0.2	2.3	56%	12%	3%	3.7
			401						
		Total	2015						

Table 2.2[d] The number of days and temperature and precipitation characteristics in the Ahr valley for different weather types, based on the period 1953-1975.

$\overline{\Delta T}$ = Mean temperature departure from normal pentad values;
$s_{\Delta T}$ = Standard deviation of ΔT;

AUTUMN

	Weather Type	Number of days	Temperature $\overline{\Delta T}$ (°C)	$s_{\Delta T}$	Percentage of days with P>1 mm	P>10 mm	P>20 mm	Mean precipitation per weather-type day (mm)
ANTICYCLONIC	+NE	67	+0.1	3.0	-			0.0
	+E	133	-0.8	3.0	5%			0.2
	+SE	18	+0.4	2.5	-	-		0.0
	+S	22	+1.6	1.8	9%	5%		0.8
	+SW	40	+1.9	2.3	3%	-		0.1
	+W	87	+1.9	2.5	8%	1%	-	0.4
	+NW	62	-0.4	3.3	6%	2%	2%	0.6
	+N	44	-0.5	3.4	2%	2%	-	0.3
		473						
INDIFFERENT	.NE	63	-0.4	2.7	13%	2%		0.7
	.E	63	-1.4	3.8	13%	3%		0.6
	.SE	29	+0.1	2.3	10%	3%		0.6
	.S	55	+2.0	2.8	22%	7%	-	1.7
	.SW	117	+1.5	2.8	31%	7%	3%	2.4
	.W	116	+1.0	2.9	25%	8%	3%	2.3
	.NW	46	-1.3	3.2	33%	7%	2%	2.4
	.N	12	-2.8	3.1	8%	-	-	0.2
		501						
CYCLONIC	-NE	32	-2.7	3.2	34%	16%	9%	4.7
	-E	31	-0.4	2.7	45%	10%	6%	3.7
	-SE	-	-	-	-	-	-	-
	-S	38	+2.4	1.9	66%	24%	8%	8.4
	-SW	173	+0.8	2.6	54%	22%	17%	5.8
	-W	119	-1.0	2.9	48%	18%	4%	4.5
	-NW	50	-2.2	3.1	50%	22%	6%	5.0
	-N	16	-3.8	3.1	44%	6%	6%	3.0
		459						
WHIRLING SITUATIONS — *High*	+H	49	+0.5	3.0	8%	2%	2%	0.5
	.H	5	-2.3	4.6	40%	-	-	1.3
	-H	1	-3.4	0.0	100%	-	-	9.5
		55						
Saddle	+X							
	.X	-	-	-	-			-
	-X	1	+0.1	0.0	100%			9.4
		1						
Low	+L	11	+1.2	4.6	-	-	-	0.0
	.L	55	+0.1	3.3	20%	5%	2%	2.1
	-L	158	-1.3	3.5	46%	19%	6%	5.1
		224						
Flat	+F	290	+1.3	2.3	4%	1%	-	0.2
	.F	61	+0.8	2.2	30%	7%	2%	2.0
	-F	28	-0.5	2.8	25%	-	-	1.0
		379						
	Total	2092						

Mean temperature departures for the 8 sectors of advection (without a distinction between cyclonic, indifferent and anticyclonic) are shown graphically in fig. 2.7. Predominantly positive temperature departures occur with the flow directions SE to W and negative departures with directions NW to E.

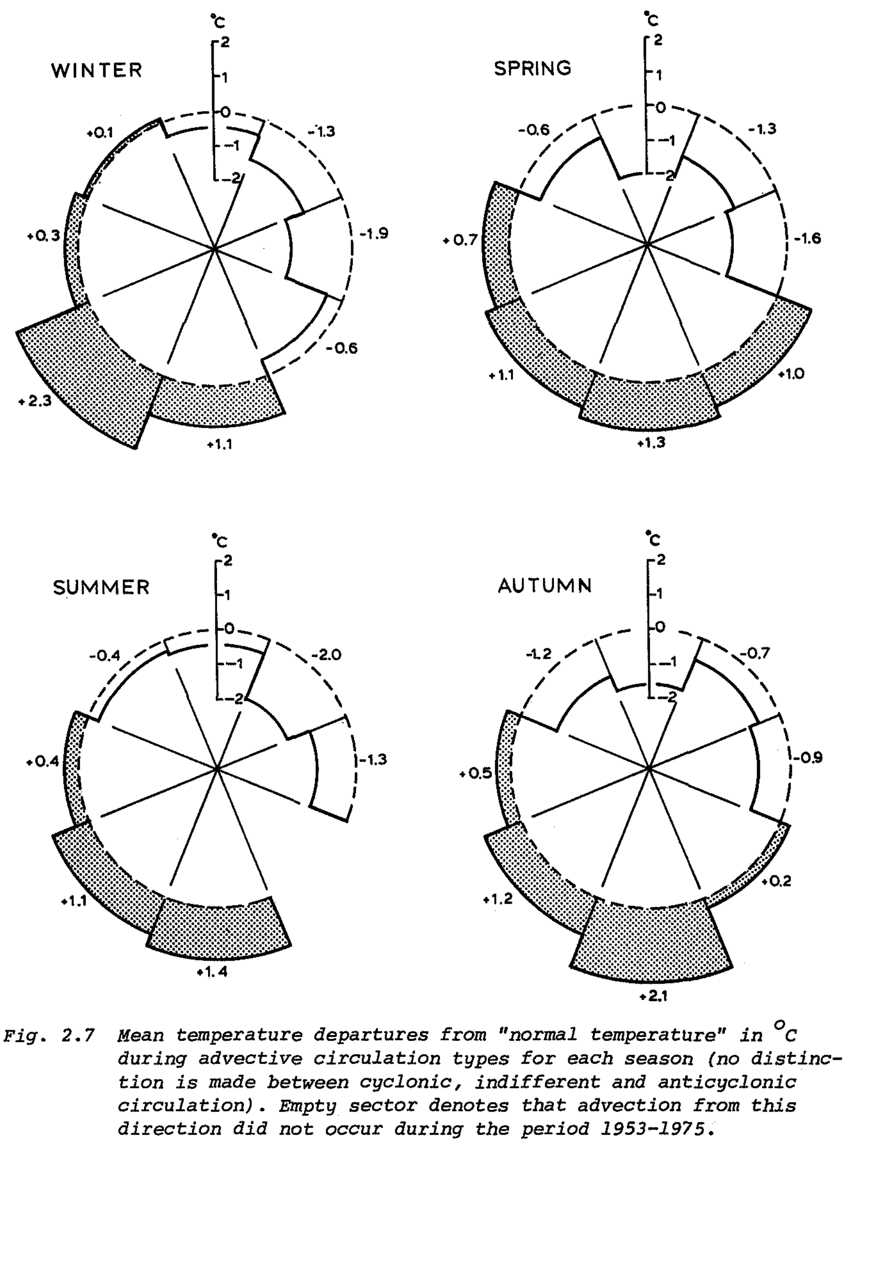


Fig. 2.7 Mean temperature departures from "normal temperature" in °C during advective circulation types for each season (no distinction is made between cyclonic, indifferent and anticyclonic circulation). Empty sector denotes that advection from this direction did not occur during the period 1953-1975.

This holds for all seasons except winter. During the winter season the distinction between relatively warm and cold air advection (i.e., positive and negative temperature departures) is of a more zonal character (east-west directed), with cold arctic and continental polar air from N to SE directions. This is from NW to E during the other seasons. The shift in winter reflects the importance of the north-west Atlantic region as a source area for relatively warm air masses.

4.4 Weather Types and Precipitation

A measure for daily mean areal precipitation for the upper-Ahr valley has been derived from the mean of stations at St.Johann (1011 m), St.Jakob (1192 m) and Rain in Taufers (1600 m) (see fig. 1.1). Rain in Taufers has been

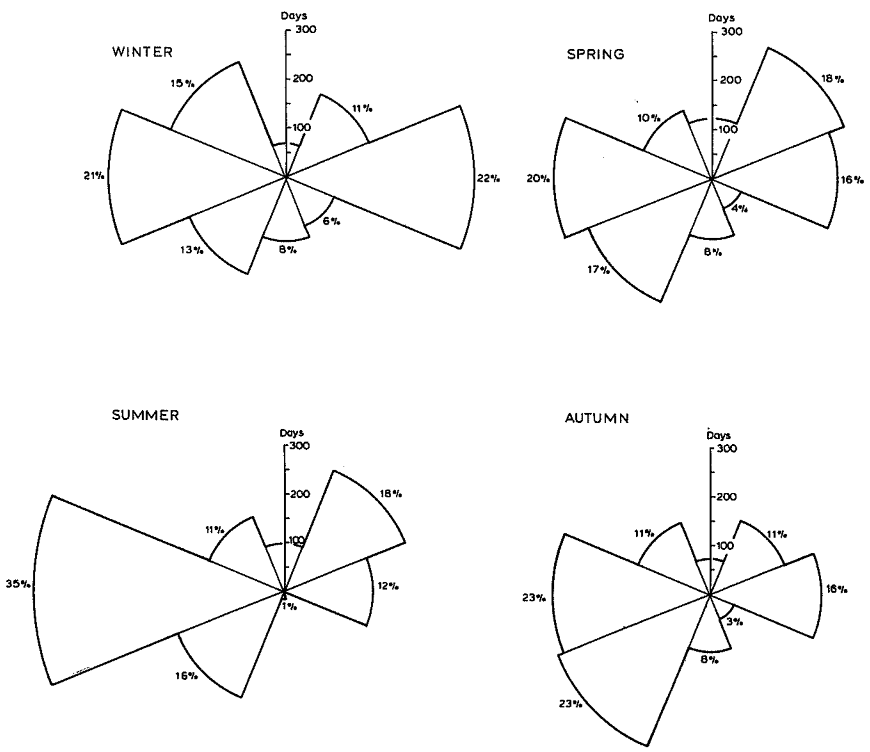
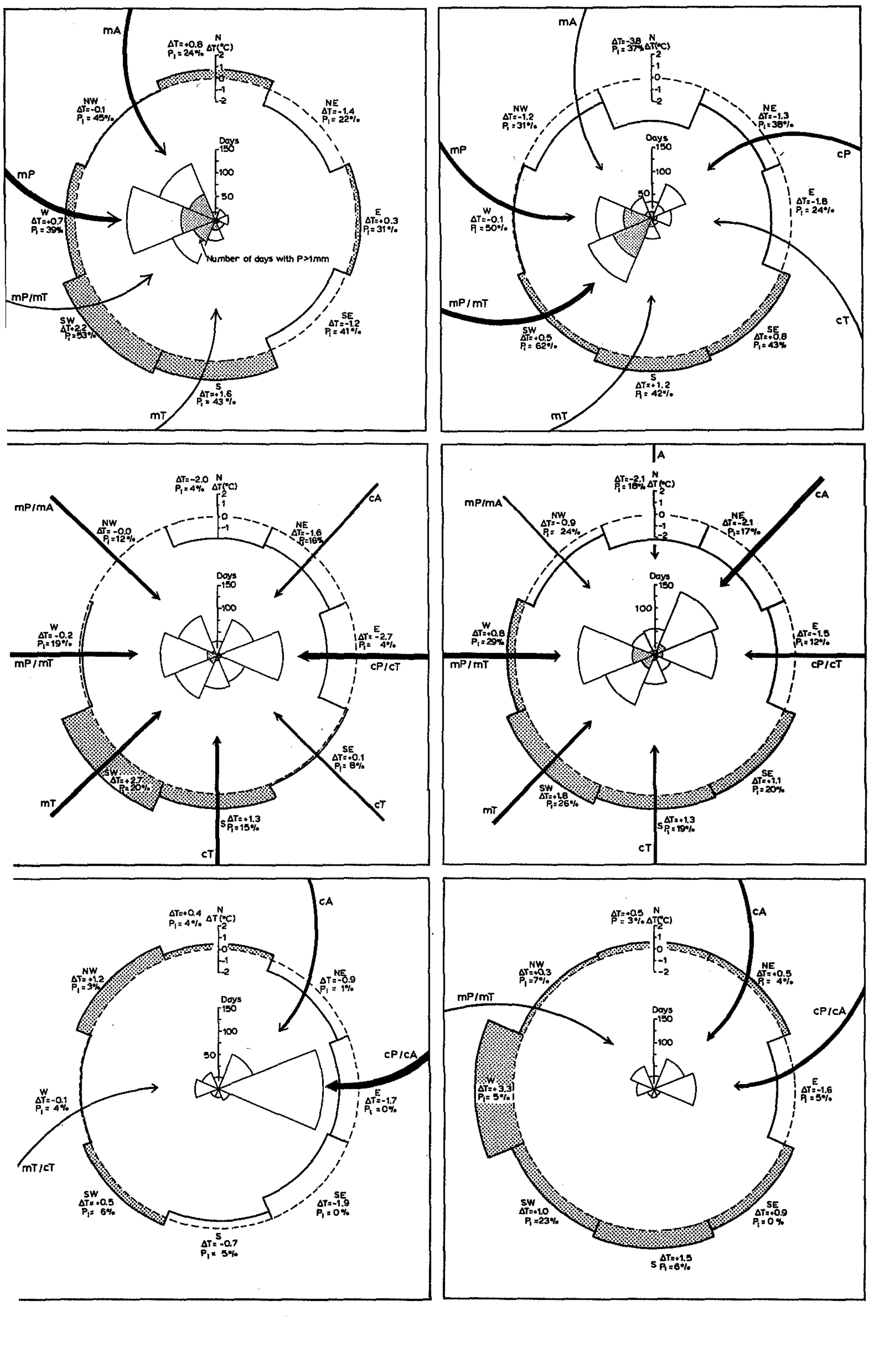


Fig. 2.8 The number of days with advective circulation and different flow directions for each season, based on the period 1953-1975

WINTER SPRING



SUMMER AUTUMN

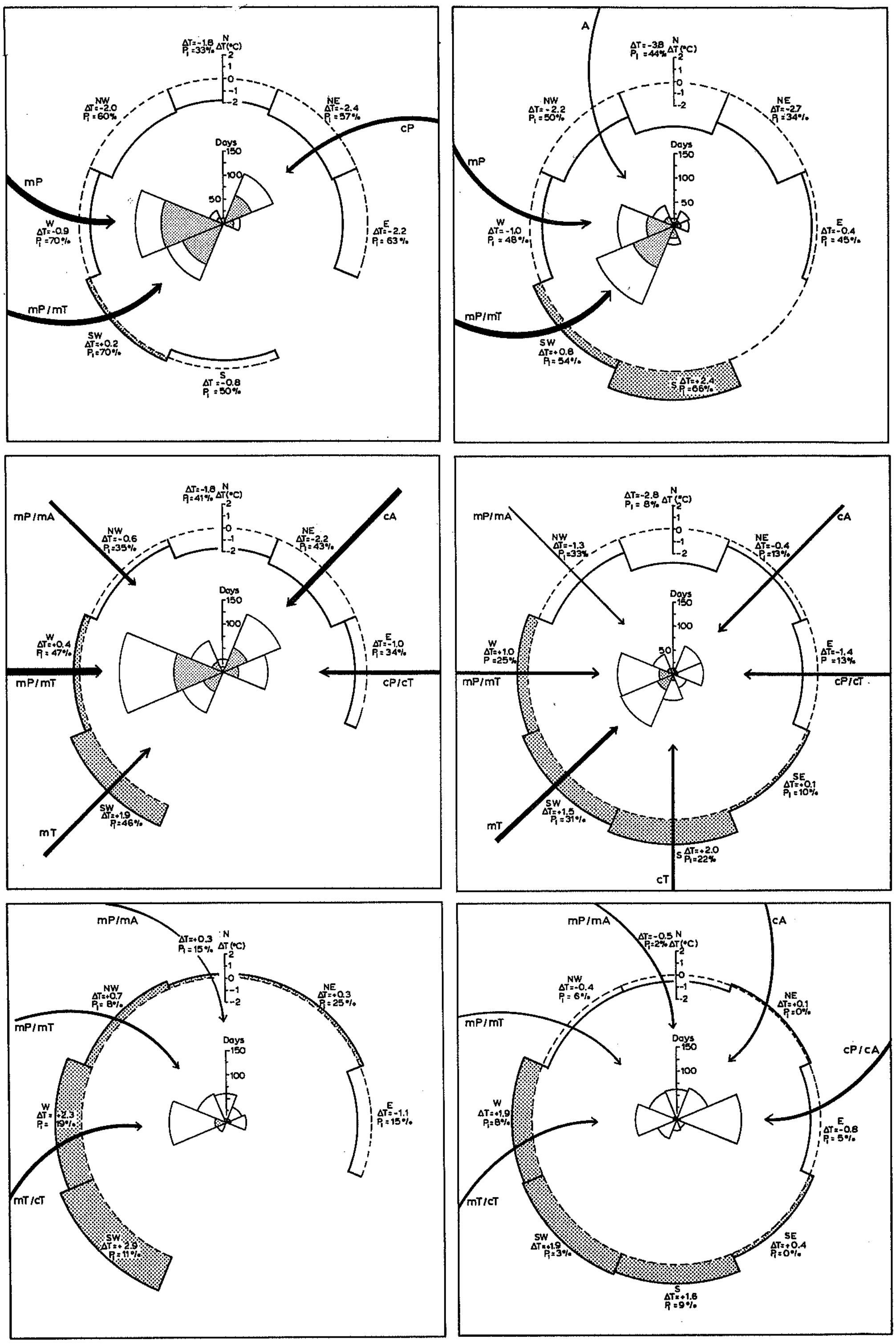


Fig. 2.9 The frequency of advective types, the number of days with precipitation > 1 mm and the temperature departures from "normal temperature" for each season. Arrows indicate the principal sources of air-mass advection; their thickness corresponds to the number of days.

implicated because both other stations show several hiatuses over the same periods. Moreover, Rain in Taufers, with its higher elevation, is probably more representative of the higher elevations in the Ahr valley (see chapter 1, fig. 1.18). For each weather type the percentage of days with precipitation > 1 mm, > 10 mm and > 20 mm has been computed for each season. The results are given in tables 2.2 (a to d). Both temperature and precipitation characteristics have been analysed on a seasonal basis in order to gain an insight into the general characteristics of air circulation and its implications for the weather. These are presented below.

4.5 Seasonal Aspects of Air Circulation

In order to present an integral picture of air circulation characteristics and their influence on the weather, temperature data and precipitation probabilities have been compiled into graphical form for each season in relation to source areas of air-mass advection. On the basis of these figures, aspects of air circulation are elucidated on a seasonal basis.

4.5.1 Winter

Frequency Distribution of Advective Circulations

During winter the general circulation is mainly of zonal character (fig.2.8). Of all days with advective circulation, 39% have an eastern component and 49% a western component in the direction of flow. A clear distinction can be made between cyclonic, indifferent and anticyclonic circulations (fig. 2.9). **Cyclonic circulation** has mainly westerly components in the direction of flow (76% of the days) and highest frequency from the W, related to the regular occurrence of cyclones over the British Isles moving in an easterly direction. **Anticyclonic circulation** has the opposite situation with mainly easterly components (68%), the highest frequency being from E and related to the existence of high pressure activity over the European continent in winter. Only 22% of the days with anticyclonic circulation have a westerly component in the direction of flow. **Indifferent circulation** is almost equally distributed over both zonal directions; 40% of the days have an easterly component and 46% a westerly component in the direction of flow.

Influences on the Weather

In broad terms, weather during the winter season is characterized by an alternation of advection by relatively cold and dry continental polar air (cP) and continental arctic air (cA) from easterly directions, and mild and moist maritime tropical air (mT) and maritime polar air (mP) from southerly and westerly directions. The differences in probability of a precipitation day (i.e., a day with $P > 1$ mm), between indifferent and cyclonic westerly circulation types is very large (fig. 2.9). Cyclonic westerly types have a probability $P > 1$ mm of about 44% and $P > 10$ mm of about 19%, against 17% and 3% respectively for indifferent types, while 70% of the total number of precipitation days occur during cyclonic circulation (see also table 2.2[a]). These differences also occur during the other seasons as will be discussed below, but they are less pronounced than during the winter season and are probably related to the lower level of condensation during winter. As a result, precipitation during indifferent NW-circulation is mainly restricted to the northern side of the Alpine mountain range, so that the southern side of the Alps remains almost free of precipitation. During cyclonic NW-circulation however, in all seasons, precipitation crosses the central Alpine mountain range and extends over the southern side of the Alps, but with a distinct increase in precipitation probability during the summer periods.

4.5.2 Spring

Frequency Distribution of Advective Circulations

Compared with the winter situation, the overall distribution of flow directions during the spring shows an increase from NE and SW and a decrease from the NW and E (fig. 2.8). **Cyclonic circulation** as a whole occurs nearly as frequently as in winter (table 2.3), but it shows an increase of SW-circulation and a decrease of W- and NW-circulations (fig. 2.9). The increase of cyclonic NE-circulations, which continues during summer, results from the higher cyclonic activity above the eastern part of the Mediterranean. **Anticyclonic circulation** shows a decrease with respect to winter from 23% to 16% (table 2.3), as a result of the decreasing high pressure activity over the Euro-Asiatic continent giving a decrease of anticyclonic E-circulation. **Indifferent circulations** show an increase from the NE which is, besides the above mentioned increase of cyclonic activity in the eastern Mediterranean, related to the formation of a strong zonal pressure-gradient between a high over the Azores and a thermal low over the Persian Gulf.

Table 2.3 The percentage distribution of Cyclonic, Indifferent and Anticyclonic advective circulation types and convective types for each season

F = flat pressure distribution X = sadddle

L = low pressure cell H = high pressure cell

		Winter	Spring	Summer	Autumn
Advective types	Cyclonic	27%	25%	24%	22%
	Indifferent	34%	37%	30%	24%
	Anticyclonic	23%	16%	16%	22%
Convective types	F	7%	11%	19%	18%
	L X	6%	9%	9%	11%
	H	3%	2%	2%	3%

Influences on the Weather

As a result of the ascending altitude of the sun during spring, the northern hemisphere is gradually warmed, further reinforced by advection of air from southerly directions. The regular interruption of this warming by invasions of polar and arctic air is characteristic for the development of weather during spring. The rising temperature of the European continent brings about a shift in the distinction between warm and cold air advection into the Alpine region. During winter this distinction was mainly of zonal character (fig. 2.7) while during spring a more meridional distinction is more appropriate; i.e., relatively warm mT- and cT-air brought from directions SE to W, and relatively cold P- and A-air from directions NW to E (see fig. 2.9). Real warm spring weather is to be expected during anticyclonic advection from southerly and westerly directions, during anticyclonic flat pressure situations (+F), as well as during high pressure situations over the Alps (+H) (see table 2.2[b]). High pressure situations, however, only occur on 2% of the days (see table 2.3).

The highest probabilities $P > 1$ mm occur during cyclonic SW- and W-circulations, and are respectively 62% and 50%. During spring, about 50% of all precipitation days occur during these cyclonic SW- and W-circulations, while 20% occur during indifferent SW- and W-circulations (see fig. 2.9).

4.5.3 Summer

Frequency Distribution of Advective Circulations

The domination of a zonal westerly circulation during summer, which occurs during 66% of all days (fig. 2.8), is related to the high pressure activity over the Azores on the one hand and the low mean pressure over the Euro-Asiatic continent on the other. Cyclonic circulations have the same frequency as during spring (table 2.3), but show an increase of W-circulation and a decrease of SW-circulation (fig. 2.9) owing to the northern shift of the depression tracks from the British Isles. Anticyclonic circulations, which also have the same frequency as in spring (table 2.3), show a shift from E to W (fig. 2.9).

Influences on the Weather

Warm periods with a low probability of precipitation occur during the same circulation types as in spring, i.e., during anticyclonic advection from directions S to W, bringing cT- and mT-air into the Alpine region (note the high frequency of +W, fig. 2.9) during anticyclonic flat pressure situations (+F) and high pressure situations (+H). The relatively high probability P > 1 mm of about 14% for these types (table 2.2^c) is connected with the occurrence of convective showers at the end of warm days, usually in the late afternoon.

The summer precipitation maximum (fig. 1.5, chapter 1) is mainly the result of an increase of cyclonic and indifferent SW- and W-circulations, which are together responsible for 60% of all precipitation days. The extremely high precipitation probabilities of 70% for cyclonic SW- and cyclonic W-circulations result (a) from the higher instability of advected air, caused by the difference in temperature between cold air at higher levels advected from higher latitudes and warm and moist air at lower levels heated under the influence of the warm Gulf Stream, and (b) from an orographic influence. The cyclonic and indifferent NE-circulations also contribute to this summer maximum, as a result of the growing cyclonic activity over the eastern part of the Mediterranean. Finally, the low pressure cells (-L) and the cyclonic flat pressure situations (-F), with a probability P > 1 mm of 66% and 56% respectively (table 2.2^c), contribute to the summer precipitation maximum.

4.5.4 Autumn

Frequency Distribution of Advective Circulations

During Autumn, the distribution of advective types shifts from S to SW and from NE to E with respect to summer (fig. 2.8), as a result of a decrease in cyclonic and indifferent NE-circulations on the one hand and an increase of anticyclonic E-circulation on the other, and is related to the building up of the winter cold high over the Euro-Asiatic continent. In autumn, the advection of continental air (cP and cA) is of anticyclonic character for about 60% of all days (fig. 2.9).

Influences on the Weather

Due to the descending altitude of the sun in the southern hemisphere, the depressions follow a more southerly track, bringing the Mediterranean and the Alps under the influence of cyclonic W-, SW- and S-circulations (fig. 2.9). The highest probabilities of precipitation days occur during cyclonic S-circulations. This type is partly responsible for the subtropical autumn- and winter-rains which are characteristic for the Mediterranean, but which affect the southern Alps as well. The southern depression-track, or Vb-track, which was first described by Van Bebber (1882) and which has been related to the high intensity rainfalls in Central-Europe, a.o. by Flohn (1954), is also of special importance for the occurrence of high intensity rainfalls in the Alps (Schwarzl, 1965, 1971, 1972). According to Reiter (1963), as cited by Barry and Perry (1973), the development of this depression track is closely related to the north-westerly flow across the western Alps leading to cyclogenesis in the region of the Gulf of Genoa. The development of a secondary low on the lee-side of the western Alps is intensified by cyclonic vorticity, created during the contact of cold polar air with warm water from the Mediterranean. Although the influence of surface heating is important in the Mediterranean region, the primary influence upon cyclogenesis is orographic, since cyclogenesis has already occurred before the cold air reaches the warm sea-water (Radinović, 1960, 1965).

The autumn rains associated with advection of air from the south form a typical element in the dynamic picture of the weather and are of special importance for flood-hydrology, not only because of the high probability and high intensities of precipitation but also because of their positive temperature departures. Cyclonic S- and SW-circulations show positive temperature departures which are on the average +1.1 °C and are thus clearly

Scheme 2.5 Selection Procedure of Hydrologically Relevant Classes of Weather-Types

Schüepp's meteorological classification of weather-types based on
surface-level flow (D) and 500 mb-level flow (d)
cyclonicity (C) and baroclinicity (B)

← First hydrologically relevant classification by rearrangement of Schüepp's weather-types on the basis of air mass advection and convective types

36 M A J O R C I R C U L A T I O N T Y P E S		
24 Advective Types	9 Whirling Types	3 Flat-Pressure Types

← Final hydrological classification and rearrangement of Schüepp's weather-types into 8 hydrological classes, on the basis of air mass advection related to source areas and convective types in combination with temperature characteristics and cyclonicity

A I R M A S S E S	*C Y C L O N I C I T Y* c Cyclonic (-)	i Indifferent (·)	a Anticyclonic (+)
I Advection of mainly continental Polar air (cP) and Arctic air (A)	I-c -N up to -E ΔT : . . – P : 26% 34% 57% 41%	I-i .N up to .E ΔT : P : 8% 15% 39% 12%	I-a +NW up to +E ΔT : . . . P : 1% 5% 14% 4%
II Advection of mainly maritime Polar air (mP) and convective types	II-c -W and -NW -L ΔT : . – P : 40% 45% 67% 47%	II-i .W and .NW .L ΔT : . . . . P : 16% 27% 43% 25%	
III Advection of mainly Tropical air (mT and cT) and convective types	III-c -SE up to -SW ΔT : + + . + P : 49% 56% 69% 56%	III-i .SE up to .SW .F, -F ΔT : + + + + P : 14% 24% 49% 26%	III-a +SE up to +W +F, all H ΔT : . + + + P : 7% 8% 14% 5%

Scheme of hydrologically relevant classes of weather types, based on a distinction on air masses and a distinction on cyclonicity. The temperature departures from normal pentad (5 days) values (ΔT) and the probability of a day with precipitation >1 mm (P) refer to the seasonal mean (winter, spring, summer and autumn)

Explanation of signs:

P = Percentage of days with precipitation >1 mm

ΔT = Temperature departure from normal pentad values (^{o}C)

$\div \quad \Delta T \geq +1\ ^{o}C$

$-1\ ^{o}C < \Delta T < +1\ ^{o}C$

$\Delta T \leq -1\ ^{o}C$

Advective types N up to NW

Convective types : H = High pressure situation

F = Flat pressure situation

L = Low pressure situation

distinguished from cyclonic W- and NW-circulations with a mean temperature departure of -1.4 °C (fig. 2.9).

4.6 Formation of Hydrologically Relevant Classes of Weather Types

Since temperature departures show significant fluctuations around their mean even within one circulation type (see tables 2.2, a to d), and since the advective types from several flow directions are relatively scarce, the determination of class boundaries is impossible on the basis of statistical criteria. It is therefore necessary to focus on general considerations with respect to flow directions and related source areas as described above in combination with temperature and precipitation characteristics.

The best way to account for the differences in precipitation probability is obviously to make a distinction between **(1) cyclonic**, **(2) indifferent** and **(3) anticyclonic** circulation types as shown in fig. 2.9. This has been used as a first **hydrologically relevant** subdivision of all advective weather-types (scheme 2.5).

On the basis of **air mass advection** and taking into account temperature departures from normal, a further distinction is made between three sectors:

- I Advection of predominantly continental Polar air (cP) and Arctic air (A)
- II Advection of predominantly maritime Polar air (mP)
- III Advection of predominantly Tropical air (mT and cT)

The cyclonic and indifferent W- and NW-circulations have been grouped together because they are closely related from a genetic point of view, notwithstanding their distinction in mean temperature departures (which is indeed pronounced during all seasons except winter (see fig. 2.9). This latter factor is of less importance for flood-hydrology than the comparable high precipitation probabilities.

For the anticyclonic advective circulations a bipartition on the basis of temperature departures appeared to be more appropriate (fig. 2.9). This use of a bipartition instead of a division in three sectors of advection reduces the total of actually distinguished and hydrologically relevant classes to 8 (scheme 2.5).

Finally, the convective types have been attributed to these 8 classes in conformity with their temperature departures and precipitation probabilities as shown in tables 2.2 (a to d).

Despite some minor exceptions, the subdivision into sectors of advection agrees rather well with the temperature characteristics of the distinguished classes. This applies to all seasons except winter. During winter, as shown in fig. 2.8, the distinction between warm and cold air advection is mainly zonal or east-west directed, with cold cP- and A-air from directions **N** to **SE**, with directions **NW** to E during all other seasons. Since during winter the input of heat from air mass advection is usually of negligible importance for the flood-hydrological regime, the winter classification has been taken in accordance with the other seasons, thus leading to a **seasonally independent classification.**

Considerations which indicate the advantages of a classification which is seasonally independent are:

- A weather type may be considered as a phenomenon which, on the whole, forms the external driving force for the hydrological behaviour, and its total impact is not determined by temperature and precipitation alone. A classification purely based on temperature and precipitation data is not realistic therefore.

- During one specific weather type the effect of the weather is dependent on the geographical position of the area concerned. A classification based on local meteorological parameters will therefore result in a different classification for different areas. In addition to providing an insight into local relations between hydrologic phenomena and weather types however, the spatial distribution of hydrologic response to individual weather types is also important. This spatial distribution does not emerge from a classification which is adapted to local conditions*.

- Seasonally dependent changes of values for meteorological parameters within one class of weather types do not find expression in a seasonally dependent classification, since the composition of classes changes from one season to another.

* *The distinction between large-scale classifications with emphasis on the spatial distribution on the one hand, and classifications of more local relevance on the other finally results in station dependent classifications (Cadez, 1957; Kirchhofer, 1976) as opposed to large-scale weather classifications.*

- A seasonally dependent classification shows unreal jumps in the frequency distribution which obstruct further interpretation and impede the general picture.

The hydrologically relevant classes which are used for a combined analysis of hydrological phenomena in the following chapter are presented in detail by scheme 2.5.

5 DURATION AND SUCCESSION OF CLASSES OF WEATHER TYPES

The duration of weather types (or classes of weather types) is an important property which should be considered in the study of hydrologic phenomena in relation to weather types. Further, it is logical to assume the existance of characteristic sequences in the development of the general circulation, reflected by a distinct preference for one weather type to be followed by another. Both the duration and the succession of weather types will be discussed in this section. The presented results refer to the 8 hydrological classes of weather types defined above.

5.1 The Frequency Distribution of Durations

The duration of a class of weather types, expressed in days, is defined as

Table 2.4 The duration of hydrological classes of weather types

Nr	Class ident.	Mean duration μ (days)	St.dev. s	Coeff. of skewness C_s	Frequency (days)	Frequency (periods)
1	I^c	3.6	1.5	0.6	438	122
2	I^i	4.3	2.2	2.6	967	227
3	I^a	4.3	2.7	1.9	1049	244
4	II^c	4.3	2.4	1.6	1369	322
5	II^i	4.1	2.0	0.9	687	167
6	III^c	4.3	2.1	1.6	987	231
7	III^i	4.9	2.5	1.4	1194	244
8	III^a	4.3	2.7	1.7	1284	299
		$\bar{\mu}$ = 4.3	$\bar{s}$ = 2.3	$\bar{C}_s$ = 1.5	Σ = 7975	Σ = 1856

the length of an uninterrupted period where each occurring weather type belongs to the class concerned. Fig. 2.10 shows for each class the distribution of durations. All distributions are skewed to the left. The coefficient of skewness (C_s) defined as:

$$C_s = \frac{a}{s^3}$$

where, $a = \dfrac{N}{(N-1)(N-2)} \sum (x - \bar{x})^3$ *(skewness parameter)*

$s = \sqrt{\frac{1}{N} \sum (x - \bar{x})^2}$ *(standard deviation)*

$N =$ number of occurrences of x

varies between 0.6 and 2.6 (see table 2.4).

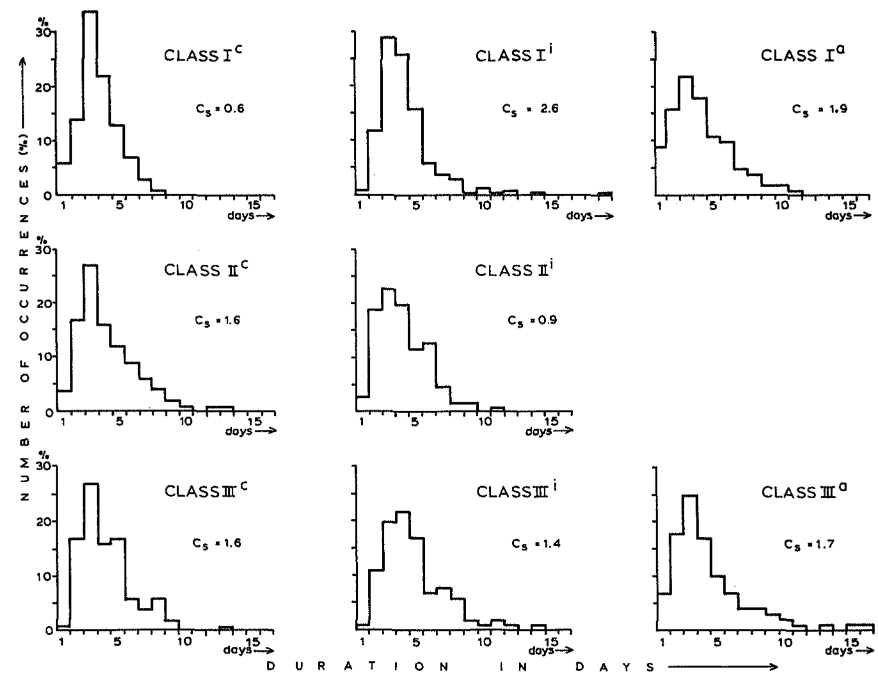


Fig. 2.10 Frequency distributions of durations (days) for the different hydrological classes of weather types (C_s = coefficient of skewness)

The mean duration varies between the narrow limits of 3.6 and 4.9 days. Except for class III-i, the highest frequency (mode) occurs with a duration of 3 days. The overall frequency distribution, summed over the classes, shows a duration of 3 days in 26% of the cases, a duration of 2 days in 16% of the cases and a duration of 4 days in 20% of the cases. A comparison of the distribution properties from table 2.4 shows that all distributions are of the same type, except for that of class I-c, which has the least persistency (lowest mean duration), probably related to the progressive dissolution of eastward-moving low pressure cells and a corresponding decrease in activity.

5.2 The Succession of one Class by Another

An analysis of the 36-type classification of weather types compiled on the basis of Schüepp's (1968) system revealed a mean duration of 4.1 days for the period 1953-1975. Mean durations are presented for different classifications in table 2.5, which are all compiled on the basis of Schüepp's system with a decreasing number of classes and ending with the present 8-type hydrological classification. The slight increase in the mean duration suggests that there is hardly any coherence between one class of weather types and the others.

Since the change from one weather type into another is expected to contain relevant information about the development of the weather, this process of succession has been analysed statistically. For this purpose it is assumed

Table 2.5 The mean duration (days) of classes of weather types for different methods of grouping, all extracted from Schüepp's classification system

Number of Classes	Description	Period	Mean duration (days)	Source
121	Schüepp (1957)	1955-1963	1.2	Fliri, 1964
33	Schüepp (1959b)	1955-1963	4.6	Fliri, 1964
36	Compiled from Schüepp (1968)	1953-1975	4.1	This thesis
11	N up to NW, Flat, High & Low*	1953-1975	4.2	
8	Hydrological classification*	1953-1975	4.3	

** Compiled from Schüepp (1968)*

that the null hypothesis of independent segregation is appropriate for the classes of weather types following each other. This means that the probability of a certain class to be in advance of the remaining classes is proportional to the observed frequencies of uninterrupted periods of these remaining classes. The observed frequencies for each class are presented in table 2.4. As such, according to table 2.4, class I-a has been followed 244 times by another class and from the null hypothesis it should have been followed 244 * 227/(1856-244) = 34 times by class I-i, and 244 * 122/(1856-244) = 18 times by class I-c, etc.

The Testing Procedure

Let $x_1,\ldots, x_8$ be the observed frequencies of uninterrupted periods of class $2,\ldots, 8$ following class 1 and let $\pi_2,\ldots, \pi_8$ be the hypothetical probabilities of a multinomial distribution with

$$\sum_{i=2}^{8} \pi_i = 1$$

To test the hypothesis $\pi_i = \pi_i^o$, $i = 2,\ldots, 8$ the following criterion is used (see also Appendix A - 3.2)

$$\chi^2 = \sum_{i=2}^{8} \frac{(x_i - n\,\pi_i)^2}{n\,\pi_i} \qquad \sum \frac{(\text{Observed - Expected})^2}{\text{Expected}}$$

or $$\chi^2 = \sum \frac{O^2}{E} - \sum O$$

where $$n : \sum_{i=2}^{8} x_i$$

which is approximately χ^2-distributed with k - 1 (k=8) degrees of freedom, if all $n\pi > 5$ (see e.g., Rao (1965), pg. 325 a.f.).

This test is applied to compare the observed distribution of followers with the theoretical distribution of followers, which is assumed to be proportional to the overall observed frequencies of the classes. If the value obtained for χ^2 exceeds the χ^2 5%-level, the null hypothesis is rejected and it is concluded that the observed frequencies of followers are not the result of random sampling. This means that there is a certain preference for the class concerned to be followed by one or more specific other classes.

Starting from the same theoretical distribution, this procedure can also be applied to test the hypothesis of whether or not the frequencies of classes that precede a specific class is the result of random sampling.

The results are presented graphically in fig. 2.11, with X^2 - values for classes following the indicated class on the right side and X^2 - values for classes preceding the indicated class on the left side. It appears that only 3 out of 8 classes have observed frequencies of followers significantly different from random sampling on a 5%-level, and thus have some preference to be followed by one or more specific other classes. The other 5 classes have no such preference.

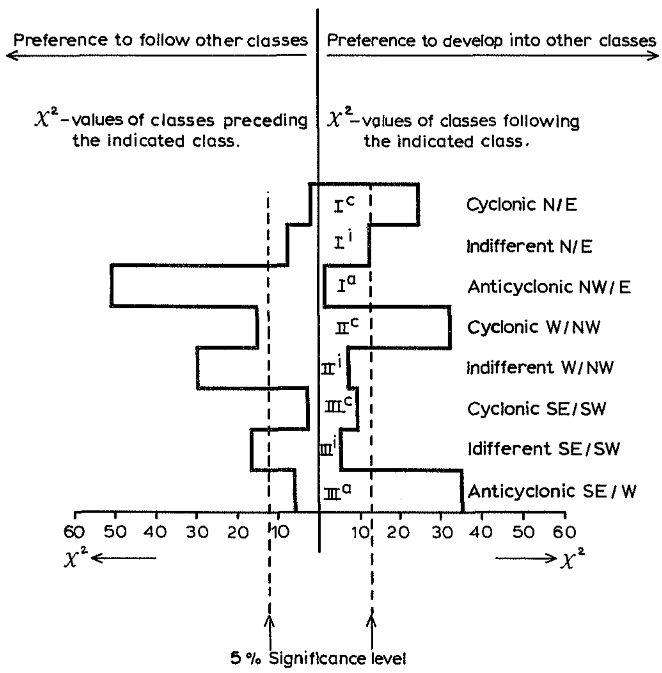


Fig. 2.11 X^2 *- values of assumed multinomial distributions of classes following the indicated classes (right side) and of classes preceding the indicated classes (left side).* X^2 *- values exceeding the indicated 5% significance level indicate that the development of the circulation from one class to another (right) and of one class from another (left) is more than by chance (i.e., not random)*

χ^2 - values of classes preceding a specific class (left side of fig. 2.11) in general show the opposite trend from that of the classes following. For example, class I-a has no preference to be followed by one or more specific other classes but has the highest preference to follow one or more specific other classes itself. Class III-a shows the reverse.

In figs. 2.12 and 2.13 the succession has been presented visually, with the expected frequencies on the the horizontal axis and the observed frequencies on the vertical axis. Fig. 2.12 shows the frequencies of the classes following others, while fig. 2.13 shows the frequencies of classes which precede

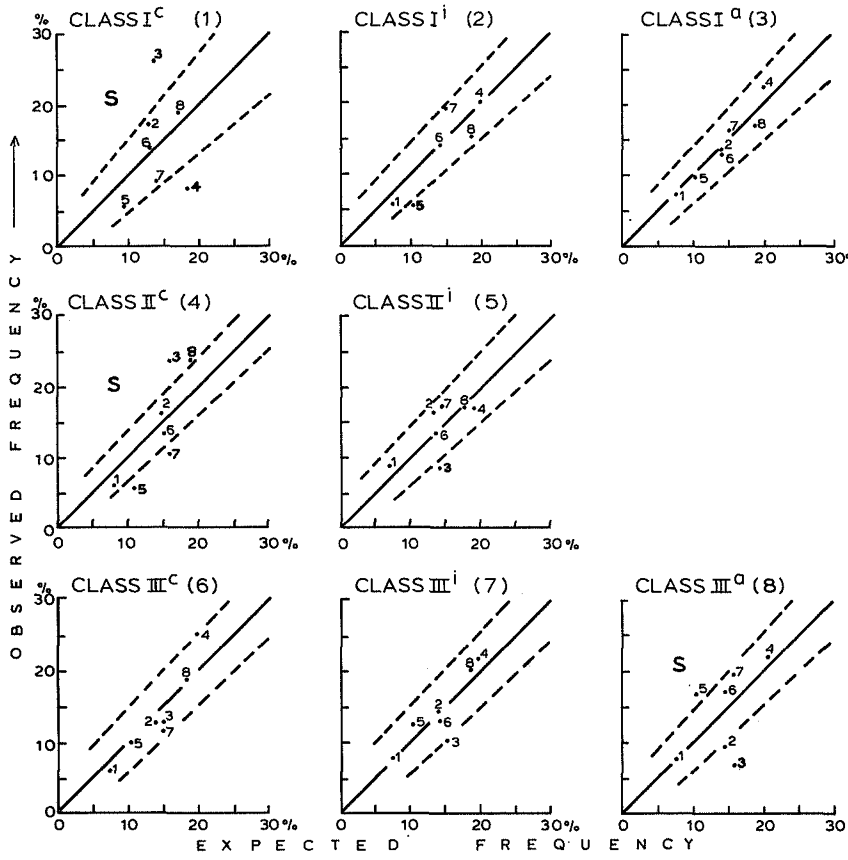


Fig. 2.12 Expected frequency (horizontal axis) versus observed frequency (vertical axis) of the classes following the indicated class (- - - - 5% significance lines)

others. For convenience, the frequencies are expressed as a percentage of the total number of successions for the class concerned. Diagrams with a distribution significantly different from random sampling are indicated with a capital **S**.

Significance lines for the 5%-level have been constructed to decide upon the significance of the individual successions. Here, the same test was applied, starting from an *alternative distribution* with two possibilities for each class being in advance, i.e., (a) being in advance of one specific class and (b) alternatively being in advance of any of the remaining classes. This is

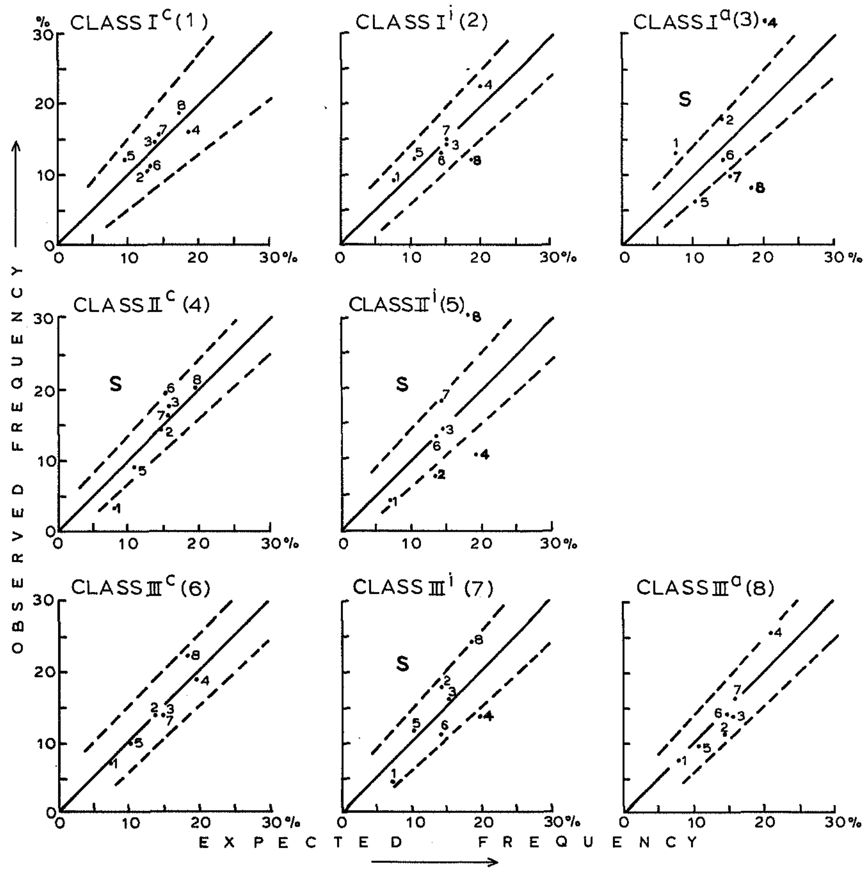


Fig. 2.13 Expected frequency (horizontal axis) versus observed frequency (vertical axis) of the classes preceding the indicated class (- - - - 5% significance lines)

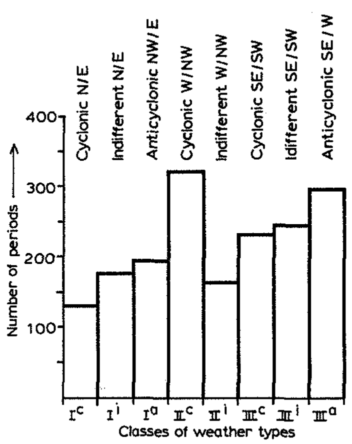


Fig. 2.14 The number of occurrences of uninterrupted periods for the different classes of weather types, based on the period 1953-1975

in accordance with the multinomial distribution, but with k-1 = 1 degree of freedom. The successions which are significantly different from random sampling are in bold type and lie beyond the significance belts.

As already learned from fig. 2.11 and further illustrated by fig. 2.12, the number of significant departures from a random segregation is small, which means that the actual distribution of followers is in general very similar to the distribution of occurrences of uninterrupted periods of each class shown in fig. 2.14. However, some general trends are still to be discerned on the basis of the significant preferences and non-preferences and will be discussed below.

5.3 Some Remarks on the Succession of the Classes

The significant departures from random sampling (segregation) are interpreted as a preference to follow c.q. to precede another class. However, as a result of the unequal frequency distribution among the classes (fig. 2.14), a significant departure does not necessarily imply the highest observed frequency of the class concerned. In order to meet the objections of the unequal distribution the actual distributions of followers are compared with the theoretically expected random distributions.

A measure for the preference (positive departure from random segregation) and non-preference (negative departure) is found by expressing the significant departures as a percentage of the expected frequency. Fig. 2.15[a] shows these preferences. It shows that the cyclonic class I-c is preferably followed by class I-a, that class II-c is preferably followed by class I-a and

III-a and that class III-a is preferably followed by class II-i. Fig. 2.15[b] shows the non-preferences.

The Anticyclonic Classes

The anticyclonic class I-a (anticyclonic NW/E-circulation) is distinguished from all others in that it has the highest preference to follow specific other classes, whereas it has the least preference to develop into some specific other class (compare fig. 2.11 with fig. 2.12 and fig. 2.13). In other words, class I-a appears to be the final stage of a sequence of successive circulation types (cycle), ending with class I-a and starting the new cycle randomly (in fact proportional to the overall distribution of fig. 2.14).

Class III-a (anticyclonic SE/W-circulation) is the opposite of class I-a since it combines the highest preference to develop into other classes with no significant preference to follow other classes. Class III-a has a preference to be followed by class II-i (indifferent W/NW-circulation) while it is preferably not followed by I-a (anticyclonic NW/E). This can be explained as follows. The Azoren high and its extensions over the Mediterranean, accompanied with anticyclonic southerly and westerly circulation over the Alps, is not preferably followed by the development of a high above Western Europe, with anticyclonic northerly circulation, but is followed rather by a weakening of the high pressure activity in the south (indifferent W/NW)under the influence of incoming cyclones from the north-west.

The Indifferent Classes

The evolution of the indifferent classes into others is on the whole not significantly different from random segregation (see fig. 2.11). From fig. 2.12 and fig. 2.15[b] however, it appears that class II-i (indifferent W/NW) is preferably not followed by anticyclonic NW/E-circulation (I-a), in agreement with the explanation above.

The Cyclonic Classes

The largest departures from random segregation occur with the cyclonic classes developing into others. This is explained to a certain extent by the evolution of the circulation during low pressure cells moving from the west towards the east. The approach of a low pressure cell is accompanied by a cyclonic SW-circulation which changes during the passage of the cell dependent on its position with respect to the Alps, into cyclonic W, cyclonic NW

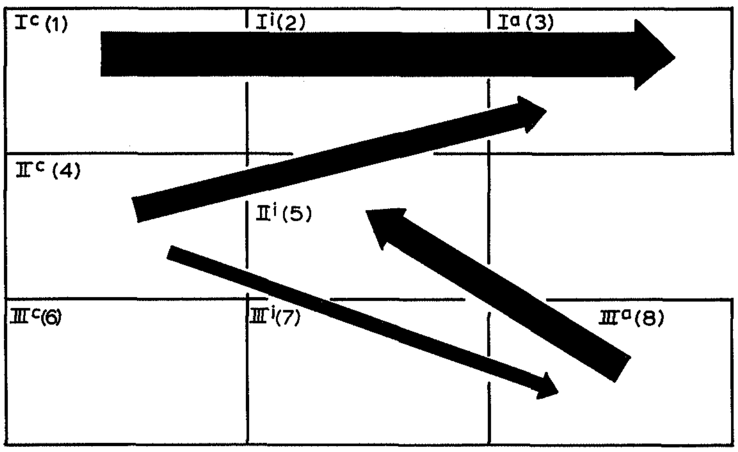


Fig. 2.15[a] *Preferential successions between classes of weather types*

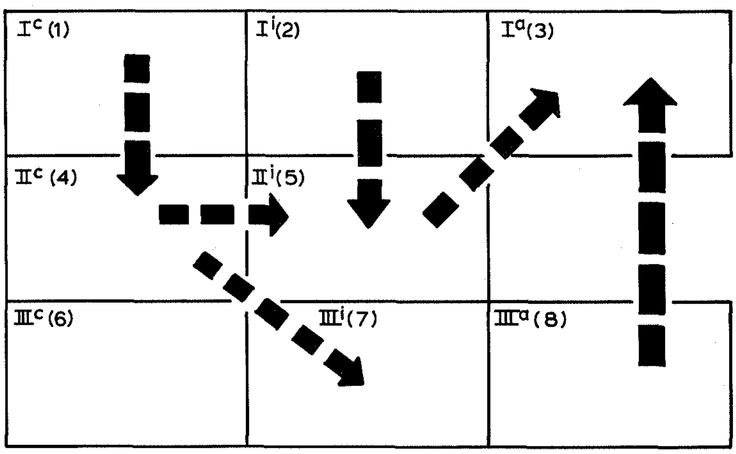


Fig. 2.15[b] *Non-preferential successions between classes of weather types*

The thickness of the arrows is in accordance with the preference (resp. non-preference), which is the departure of the actual observed frequency from the random expected frequency, expressed as a percentage of the expected frequency .

and finally into cyclonic N followed by a reduced influence of the low pressure cell. This probably explains why cyclonic N/E-circulation (I-c) as the final stage of the eastward-moving low pressure cells, and cyclonic W/NW (II-c) to a lesser extent, are preferably followed by anticyclonic NW/E-circulation (I-a).

5.4 The Frequency of Preceding Classes

Despite the fact that for certain classes there exists a significant preference to be followed by others, the evolution of one class into another is still from a statistical point of view too much a random process to form the basis of a prediction tool for the development of the circulation. However, to study discharge phenomena in relation to (classes of) weather types, antecedent conditions are of crucial importance. These antecedent conditions controlling the hydrologic processes are mainly governed by the impact of the preceding weather conditions, so that insight into their distribution is necessary in order to explain discharge phenomena in relation to weather types. In table 2.6 the observed predecessors of each class have been summed for cyclonic, indifferent and anticyclonic classes separately. An important distinction is that class I-i (indifferent N/E-circulation) is most frequently preceded by cyclonic classes, whereas class III-i (indifferent SE/SW-circulation and class II-i (indifferent W/NW-circulation) are most frequently preceded by anticyclonic classes.

Table 2.6 The frequency (%) of preceding classes, grouped for cyclonic, indifferent and anticyclonic classes

Following Classes	Preceding Classes (%)		
	Cyclonic	Indifferent	Anticyclonic
I-c	33.6	38.5	27.9
II-c	22.7	39.7	37.6
III-c	26.4	37.7	35.9
I-i	45.4	27.7	26.9
II-i	28.8	26.3	44.9
III-i	29.5	29.9	40.6
I-a	57.0	34.4	8.6
III-a	48.2	37.8	14.0

CHAPTER III

ANALYSIS OF WEATHER-TYPE HYDROLOGIC PHENOMENA

. INTRODUCTION

General circulation and characteristics of the different weather types in terms of precipitation and temperature have been discussed extensively in the previous chapter, particularly with regard to their dependency on the time of year. This led to the formation of eight hydrologically relevant classes of weather types which form the basis of runoff-forecasting in the next chapter. In this chapter, weather-type hydrologic phenomena are analysed with special reference to the combined effect of weather types on the one hand and the hydrologic system of the catchment on the other.

2 THE APPROACH

In this approach the (classes of) weather types are regarded as the driving forces of the hydrological sub-systems (as discussed in chapter I) and together form the complex hydrologic system of the catchment. These sub-systems are all in a different manner related to the weather types. Therefore, the basic idea is that (notwithstanding the great variability of runoff) each class of weather types has its own characteristic population of daily runoff data and sequences of daily runoff. In order to obtain a better insight into the combined effect of weather types working on the complex hydrologic system, several aspects of runoff have been analysed both with respect to the distribution of daily runoff occurrences as well as with respect to their time-sequence.

Because the hydrological characteristics of the distinguished systems and their relations with the weather types are strongly dependent on the time of year, the analyses have been performed separately for each month of the year.

The following computations have been performed for each class of weather types.

A. WITH RESPECT TO THE DISTRIBUTION OF DAILY RUNOFF OCCURRENCES

. MEAN DAILY RUNOFF has been computed for each month by averaging daily runoff over the days with the particular class.

2. UNBIASED VARIANCE as an estimate of the scatter of the individual daily runoff values within each class around the population mean of that class, defined as

$$s_q^2 = \frac{1}{n-1} \sum_{i=1}^{n} (q_i - \bar{q})^2$$

where, q_i = i^{th} observed daily runoff in the particular month and during the particular class of weather types

n = number of occurrences

B. WITH RESPECT TO THE CHARACTERISTICS OF THE TIME-SEQUENCES

3. MEAN DAY-TO-DAY CHANGES OF RUNOFF. This parameter was chosen to represent the influence of the different weather types on the total regime curve in terms of increase or decrease of runoff on the average.

4. COEFFICIENT OF VARIATION (C_v) of the day-to-day changes of runoff for each class, defined as the standard deviation of the changes divided by the overall monthly mean daily runoff, or

$$C_v = \frac{\sqrt{s_{\Delta q}^2}}{\bar{Q}}$$

where, $s_{\Delta q}^2$ = unbiased variance of the day-to-day changes (Δq) in the particular month and during the particular class of weather types

$\bar{Q}$ = mean daily runoff in the particular month over the period (1953-1975) without reference to a particular class of weather types

5. TREND ANALYSIS of daily runoff during uninterrupted periods of the same class of weather types. All day-to-day runoff changes of uninterrupted periods were analysed (a) as a function of the time elapsed since the start of that particular weather-class and (b) as a function of the magnitude of runoff.

6. ANALYSIS OF VARIANCE. In order to compare the influence of the different weather types on the population of daily runoff occurrences use is made of the analysis of variance.

A comparison of several sets of runoff occurrences may be performed by means of the analysis of variance in order to conclude whether or not the sets are coming from the same population. The analysis is based on the F-test (see e.g., Hald, 1965).

Consider k samples of n_k occurrences drawn randomly from a normally distributed population with a mean ξ and a variance σ^2. The comparison of the k samples then results in k sample means and k sample variances. If the i^{th} sample has n_i occurrences, then each occurrence is denoted $q_{i,j}$ ($i=1,\ldots,k$; $j=1,\ldots,n_i$), and the sum of all observations is

$$N = \sum_{i=1}^{k} n_i$$

The mean of all $q_{i,j}$ is denoted by $\bar{q}$ and the mean of the i^{th} sample is $\bar{q}_i$. The total estimated variance s^2 is split into the variation s_E^2 between the samples (external variance) and the variation s_I^2 within the samples (internal variance) according to:

$$(N-1)\ s^2 = (k-1)\ s_E^2 + (N-k)\ s_I^2$$

where

$$(N-1)\ s^2 = \sum_{i=1}^{k} \sum_{j=1}^{n_i} (q_{i,j} - \bar{q})^2$$

$$(k-1)\ s_E^2 = \sum_{i=1}^{k} n_i\ (\bar{q}_i - \bar{q})^2$$

$$(N-k)\ s_I^2 = \sum_{i=1}^{k} \sum_{j=1}^{n_i} (q_{i,j} - \bar{q}_i)^2$$

The hypothesis that the different samples come from the same population is tested at a significance level p using Fischer's F-test, where

$$F^c = \frac{s_E^2}{s_I^2}$$

with $f_1 = (k-1)$ and $f_2 = (N-k)$ degrees of freedom. The hypothesis is rejected if

$$\frac{s_E^2}{s_I^2} \geqq F^t(p, f_1, f_2)$$

This analysis of variance assumes the runoff-occurrences to be normally distributed and the samples to be drawn independently from populations with the same standard deviations.

3 COMPARISON OF WEATHER-TYPE RUNOFF PHENOMENA AND INTERPRETATION

3.1 Monthly Mean Daily Runoff

Starting from the basic concept that the weather types are the driving force for the hydrologic systems and consequently have their own characteristic population of daily runoff values and sequences, it is to be expected that differences in mean runoff will be evident for the distinguished classes of weather types. The large differences in mean daily precipitation and mean daily temperature between the selected anticyclonic classes I-a (anticyclonic N/E) and III-a (anticyclonic SE/W) on the one hand and the combined cyclonic classes II-c (cyclonic W/NW) and III-c (cyclonic SE/SW) on the other, are shown in fig. 3.1 and fig. 3.2.* However, these differences are much less pronounced in the mean runoff curves of fig. 3.3. Although such small differences in mean runoff suggest that the populations of runoff occurrences within each class of weather types might be not significantly different, such a conclusion cannot be drawn without regard to the estimated variances of the populations from analysis of variance.

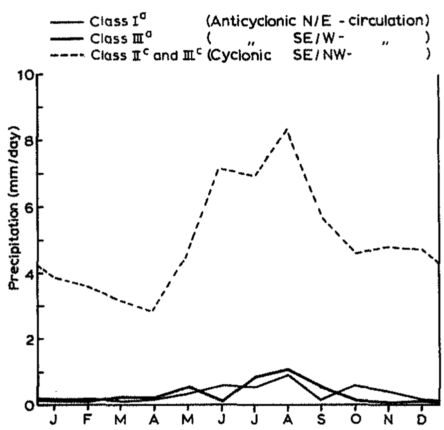


Fig. 3.1 Mean monthly precipitation at St.Jakob (1192 m a.s.l.) in the Ahr valley, for different classes of weather types (period 1953-1975)

* *Indifferent classes can be regarded as mixing forms between anticyclonic and cyclonic circulations and have been omitted in this example.*

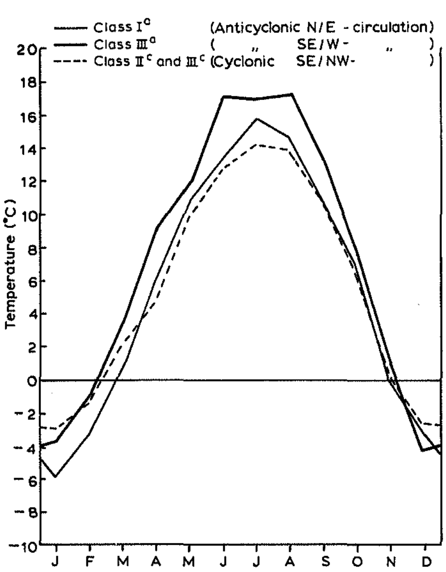


Fig. 3.2 Mean monthly temperature at Antholz (1236 m a.s.l.) in an adjacent valley of the area of investigation, for different classes of weather types (period 1953-1975)

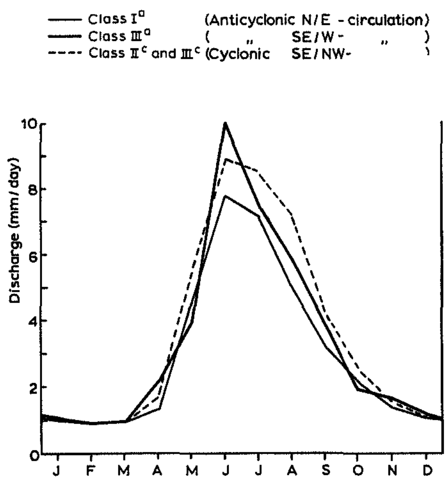


Fig. 3.3 Mean monthly discharge of the river Ahr at Steinhaus for different classes of weather types (period 1953-1975)

3.2 Analysis of Variance of Runoff between the Classes of Weather Types

In order to decide upon the influence of the distinguished classes of weather types on the population of daily runoff, use is made of the analysis of variance outlined above.

As the normal course of runoff itself (fig. 3.3) is responsible for part of the variance even within each month and can be assumed as independent of the weather types, the departures from this normal course have been used instead of the daily runoff values themselves. These are denoted by daily runoff departures, q'. The daily runoff departures in each month are distributed over the different classes of weather types, each regarded as a sample. Thus, the estimated variation $(s_{q'})^2$ is split into the variation $(s_{q'(I)})^2$ within the samples *(internal variance)* and the variation $(s_{q'(E)})^2$ between the samples *(external variance)*.

To test the hypothesis that the different samples of daily runoff departures - each belonging to a different class of weather types - are coming from the same population, i.e., the individual classes of weather types themselves have no significant influence on the distribution, Fischer's F-test has been used, where

$$F^c = \frac{s^2_{q'(E)}}{s^2_{q'(I)}}$$

with f_1, f_2 degrees of freedom and at the 95% significance level. The hypothesis is rejected if

$$F^c \geqq F^t(95\%, f_1, f_2)$$

The results of the computations, applied to the selected classes I-a, III-a and the combined classes II-c and III-c, are shown in table 3.1. It appears that for all months the computed F-values are smaller than the theoretical F-values at the 95% level.

INTERPRETATION

To interpret the results we must consider the above mentioned assumptions within the analysis of variance. Although the test shows that the populations of runoff departures during the different selected classes of weather types

Table 3.1 Analysis of Variance of Daily Runoff (mm) between three selected Classes of Weather Types, i.e.:

Class I-a : Anticyclonic N/E-circulation
Class III-a : Anticyclonic SE/W-circulation
Class II-c and III-c : Cyclonic SE/NW-circulation

	Total		External		Internal		F-values	
Month	N-1	s^2	k-1 (f_1)	s_E^2	N-k (f_2)	s_I^2	F^c	F^t (95%, f_1, f_2)
1	78	0.04	2	0.01	76	0.04	0.3	3.1
2	70	0.04	2	0.01	68	0.04	0.1	3.1
3	69	0.14	2	0.04	67	0.14	0.3	3.1
4	73	2.02	2	3.54	71	1.98	1.8	3.1
5	82	18.64	2	18.44	80	18.65	1.0	3.1
6	77	38.11	2	43.22	75	37.97	0.9	3.1
7	88	16.97	2	43.30	86	16.36	2.6	3.1
8	82	13.83	2	25.83	80	13.52	1.9	3.1
9	94	6.32	2	3.37	92	6.39	0.5	3.1
10	101	1.86	2	0.86	99	1.84	0.5	3.1
11	80	0.86	2	1.76	78	0.84	2.1	3.1
12	84	0.27	2	0.05	82	0.28	0.2	3.1

are not significantly different, we may not conclude that the classes have no influence on runoff phenomena because this may simply be caused by the assumptions which have not been satisfied. For example, the assumption of independence is obviously not satisfied (1) because the runoff is highly autocorrelated - this point will be discussed later - and (2) because of the different frequencies of preceding classes of weather types (chapter 2). Therefore, rather than considering the population of runoff departures, we will focus on the character of runoff during the different classes of weather types on the one hand and on the influence of other factors, not related to the weather types, on the other.

3.3 Comparison of Variability and Day-to-Day Changes within each Class

Also, the following analyses have not been performed for all eight classes. A selection has again been made of (1) anticyclonic N/E-circulation (I-a), (2) anticyclonic SE/W-circulation (III-a) and (3) the combined cyclonic classes II-c and III-c (cyclonic SE/NW-circulation). The indifferent classes which, in fact, form hybrid types between anticyclonic and cyclonic types have again been omitted.

The different character of runoff during the different classes appears very clearly from fig. 3.4 which gives the coefficient of variation (variability) for discharge changes for each month. The figure shows the higher variability during cyclonic weather classes (II-c and III-c), especially demonstrating their pronounced variability during late summer. The different character is still better expressed by the mean day-to-day changes of daily runoff

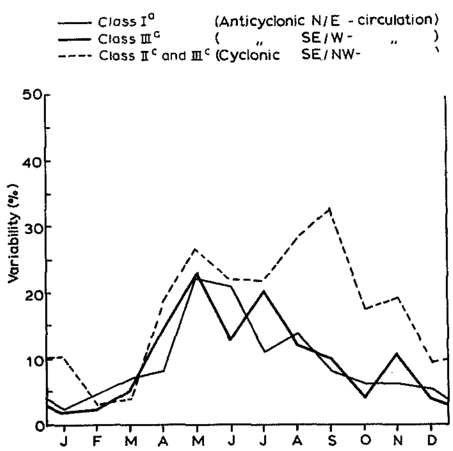


Fig. 3.4 Mean monthly variability of daily discharge changes of the river Ahr at Steinhaus, for different classes of weather types (Period 1953-1975; for explanation see text)

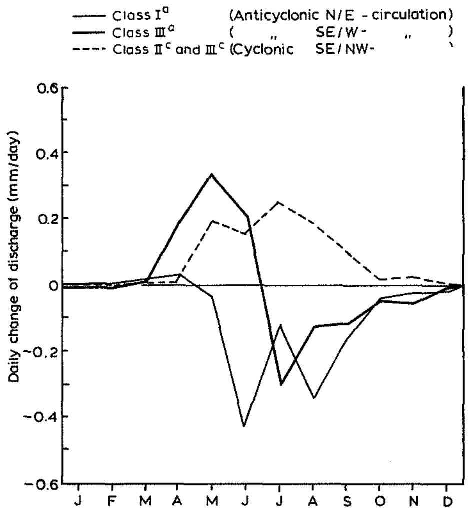


Fig. 3.5 Mean of daily discharge changes of the river Ahr at Steinhaus, for each month and for different classes of weather types (period 1953-1975; for explanation see text)

given by fig. 3.5. During anticyclonic N/E-circulation (I-a), Δq shows negative values throughout almost the whole year (discharge falls on the average). However, during cyclonic SE/NW-circulation (II-c and III-c), Δq shows positive values throughout the year (discharge increases on the average) while the differences in mean runoff during both classes are comparatively small. The runoff during the weather types preceding the anticyclonic N/E-circulation (I-a) is obviously responsible for this mean runoff rather than the particular weather type itself. Indeed, it appeared from the analysis of preceding classes that class I-a is preceded in 57% of the cases by cyclonic classes and in 44% of the cases by the combined classes (II-c and III-c) which show positive values of Δq throughout the year. The antecedent conditions apparently have an extreme influence on the magnitude and the character of runoff during the different weather types.

3.4 Analysis of Variance of Runoff within the Classes of Weather Types

The role of antecedent conditions with respect to the runoff phenomena during the different classes of weather types is probably best illustrated from the analysis of variance of daily runoff departures within each class of weather types.

The variance of a population of discharges for a particular class is determined by variations which can generally be split into two groups, i.e.,

a) variations governed by the reaction of the systems to precipitation and temperature, occurring within the periods of the same class;

b) variations resulting from different magnitudes of runoff during periods of the same class.

According to these two groups the total variance is again split into the internal variance (group a) and an external variance (group b).
The internal variance is expected to be primarily governed by the particular weather type and is therefore assumed to be characteristic for the combined effect of weather type and hydrologic system-conditions.
The external variance is expected to be primarily governed by factors not related to the particular weather type and may in principle be the consequence of the following two factors:

b') The characteristic times* of the systems contributing to runoff at the beginning of a particular weather type are so large that the particular weather type and corresponding active hydrological systems are unable to eliminate this influence during the lifetime of that class, in order to reach a runoff level which is characteristic for that weather type and the active systems.

b'') The antecedent hydrological conditions vary from year to year in such a manner that even if the above mentioned characteristic runoff (b') is reached, its magnitude is still governed by the hydrologic conditions (snow cover etc.).

The results of the computations are presented in table 3.2. The hypothesis that the samples of the same weather type are from the same population is again tested using Fischer's F-test at a 95% confidence level.

In table 3.2 the theoretical F-values and the computed F-values have been presented for each month of the year and for each of the selected classes of weather types. The hypothesis is again rejected if

$$F^c \geqq F^t(95\%, f_1, f_2)$$

* *The characteristic time is a measure of the rate with which the runoff from the system concerned decreases during a period without input (meltwater or rainfall).*

Table 3.2 Analysis of Variance of Daily Runoff (mm) within three Classes of Weather-Types

Class I[a] (Anticyclonic N/E-circulation)

Month	Total		External		Internal		F-values	
	N-1	s^2	k-1 (f_1)	s_E^2	N-k (f_2)	s_I^2	F^c	F^t (95%, f_1, f_2)
1	160	0.02	24	0.14	136	0.00	109.0	1.6
2	135	0.01	24	0.07	111	0.00	38.7	1.6
3	96	0.04	19	0.20	77	0.01	29.7	1.7
4	105	0.47	22	2.10	83	0.03	62.4	1.7
5	70	4.97	16	17.48	54	1.26	13.9	1.9
6	64	6.51	15	15.37	49	3.79	4.1	1.9
7	113	4.17	23	18.44	90	0.52	35.4	1.7
8	79	3.24	16	13.90	63	0.53	26.2	1.8
9	102	1.33	18	6.69	84	0.18	38.1	1.7
10	138	0.55	24	3.03	114	0.02	128.5	1.7
11	134	0.11	19	0.67	115	0.02	43.1	1.7
12	144	0.07	26	0.39	118	0.01	75.6	1.6

Class III[a] (Anticyclonic SE/W-circulation)

Month	Total		External		Internal		F-values	
	N-1	s^2	k-1 (f_1)	s_E^2	N-k (f_2)	s_I^2	F^c	F^t (95%, f_1, f_2)
1	90	0.02	20	0.09	70	0.00	213.2	1.7
2	84	0.02	18	0.09	66	0.00	127.9	1.7
3	127	0.05	21	0.30	106	0.00	79.5	1.8
4	72	1.43	15	5.65	57	0.32	17.9	1.6
5	101	6.06	23	20.04	78	1.94	10.3	1.7
6	106	17.75	22	77.66	84	2.06	37.7	1.7
7	110	6.30	23	21.63	87	2.25	9.6	1.7
8	164	2.26	29	10.67	135	0.46	23.4	1.5
9	228	1.70	39	8.90	189	0.22	40.6	1.4
10	249	0.83	38	3.01	211	0.03	109.7	1.4
11	123	0.26	20	1.38	103	0.04	38.0	1.7
12	97	0.07	20	0.33	77	0.00	184.4	1.7

Table 3.2 (cont.)

Class II^c and III^c (Cyclonic SE/NW-circulation)

Month	Total		External		Internal		F-values	
	N-1	s^2	k-1 (f_1)	s_E^2	N-k (f_2)	s_I^2	F^c	F^t (95%, f_1, f_2)
1	205	0.01	36	0.07	169	0.00	66.5	1.5
2	153	0.01	27	0.06	126	0.00	36.7	1.5
3	177	0.03	28	0.17	149	0.00	64.6	1.5
4	202	0.54	34	2.52	168	0.13	19.1	1.4
5	227	9.16	41	37.58	186	2.89	13.0	1.4
6	197	12.43	38	49.30	159	3.62	13.6	1.4
7	188	7.75	42	25.08	146	2.76	9.1	1.4
8	205	10.25	35	37.57	170	4.62	8.1	1.4
9	179	3.02	35	9.86	144	1.36	7.3	1.4
10	195	0.73	38	2.71	157	0.25	10.9	1.4
11	267	0.39	39	1.94	228	0.12	16.3	1.4
12	257	0.06	39	0.34	218	0.01	27.9	1.4

INTERPRETATION

As in the foregoing analysis of variance, also here we must consider the basic assumptions of the analysis. In addition to the above mentioned arguments, in this case the assumption that the samples consist of independent elements is far from satisfied. On the contrary, the elements of daily runoff occurrences are highly autocorrelated and related to the characteristic times of the hydrologic systems. This probably explains the extreme F-values in table 3.2.

From table 3.2 it follows that for all weather types $F^c \gg F^t$, from which it can be deduced that the weather types themselves are indeed a minor influence on the magnitude of runoff and that the factors mentioned under b (b' and b'') are the main factors which explain the magnitude of runoff. In other words, the magnitude of runoff during a particular weather type is largely governed by AUTOCORRELATION (related to the characteristic times of the passive systems which were active during the preceding class, and thus related to the preceding weather class) and by ANTECEDENT CONDITIONS (probably related mainly to the extent of snow-cover and physical properties of the snow-pack) rather than by the weather type itself.

3.5 Trend Analysis

The most important conclusion to be drawn from the above analysis of variance is that both antecedent conditons and the characteristic times of the systems are of particular importance for the magnitude of runoff during different classes of weather types. It also appeared that the antecedent conditions, related to the active hydrologic systems during the preceding class of weather types, are of importance for the character of runoff during a particular class.

Therefore, the influence of antecedent conditions on the character of runoff is expected to decrease proportionally as the duration of a class of weather types increases, and thus runoff is expected to be governed in a progressive measure by the corresponding active hydrologic systems.

In order to investigate the influence of antecedent conditions on the character of runoff during uninterrupted periods of the same weather class, all day-to-day changes were analysed

a) as a function of the time elapsed since the start of that particular weather class, and

b) as a function of the magnitude of runoff.

This trend analysis has been performed for all days ($\Delta q = q_n - q_{n-1}$), for $n = 1,\dots,6$ where q_n is the mean runoff during the n^{th} day of the sequence. Fig. 3.6 gives an example for the anticyclonic SE/W-circulation in July (period 1953-1975), and shows the tendency of runoff to increase at low runoff levels and to fall at high levels. By means of linear regression (see Appendix A), the average day-to-day change has been estimated at three levels, i.e., for $\overline{q}_{n-1}$, $(\overline{q}_{n-1} + s_q)$ and $(\overline{q}_{n-1} - s_q)$, where $\overline{q}_{n-1}$ and s_q are respectively the mean runoff and the standard deviation of daily runoff on day $n-1$.

Because the populations of daily runoff values appeared not to be distributed normally, this interval does not indicate the actual distribution about the mean but is merely meant to indicate an arbitrary level above and below the mean. Fig. 3.7 gives in this manner the average trend of daily runoff

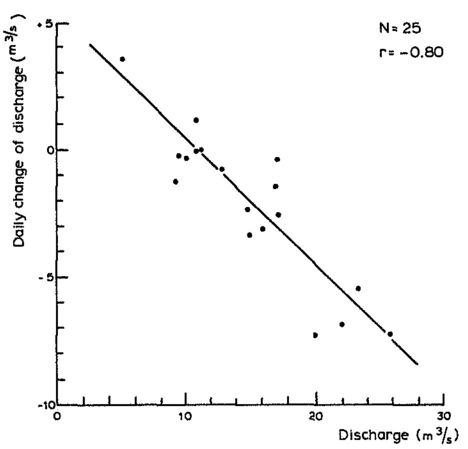


Fig. 3.6 The relation between the change in discharge (vertical scale) and the mean discharge of the preceding day (horizontal scale) in July during anticyclonic SE/W-circulation (class III-a)

during uninterrupted periods of the same class of weather types. The irregularities in this figure result from the reduction of the occurrences with increasing duration. The same analysis has been performed for the mean daily temperatures at Antholz shown in fig. 3.8.

INTERPRETATION

In fig. 3.7 and fig. 3.8 the mean course of runoff and temperature has been presented for both anticyclonic classes I-a and III-a. Both classes show an average increase of temperature on all levels ($\bar{T}$ and $\bar{T} \pm s_T$) as expected for these classes.

A comparison with the course of daily runoff shows that the runoff does not demonstrate this continuous increase on all levels, but, on the contrary, displays a distinct dependency on the time elapsed since the start of these particular classes. The expected increase of runoff does not become manifest until after a couple of days and is generally preceded by a period of decreasing runoff.

Class III-a in particular shows a characteristic course which generally occurs during all months from May till August and in which the following division can be made:

$0 \longrightarrow 1^{st}$ day: High runoff values show a tendency to decrease while low runoff values tend to increase. Runoff decreases on average. Here we are dealing with a situation where runoff is governed by

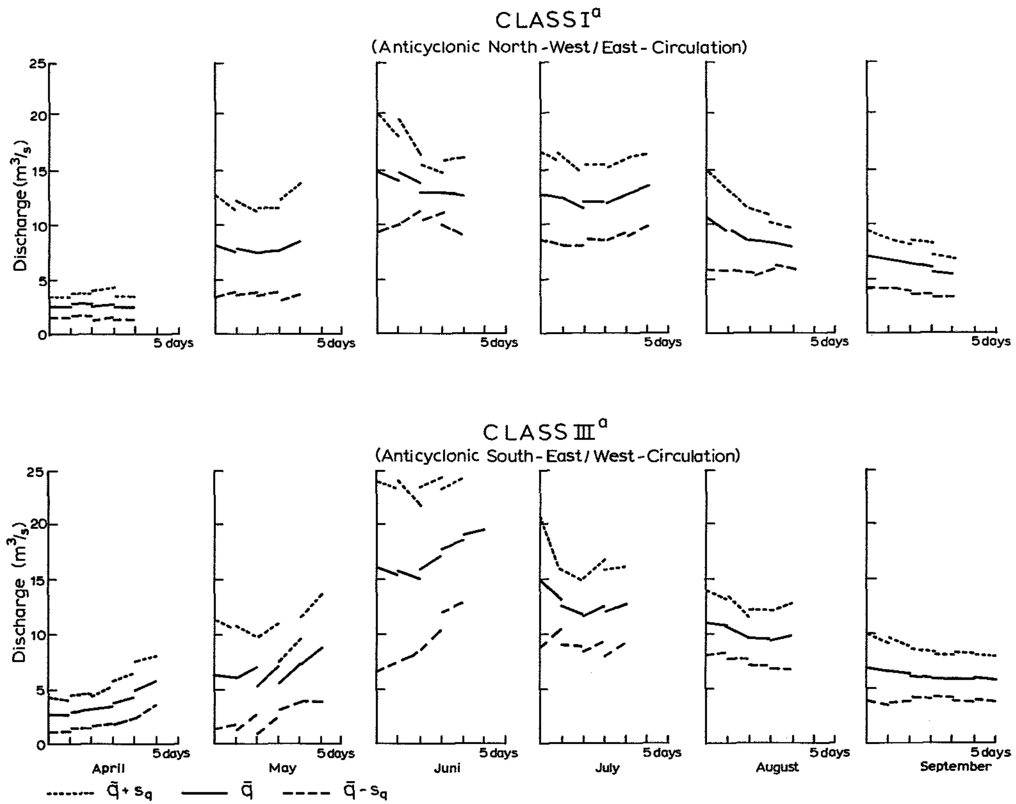


Fig. 3.7 The average course of runoff at Steinhaus (1953-1975) during five successive days, at three levels

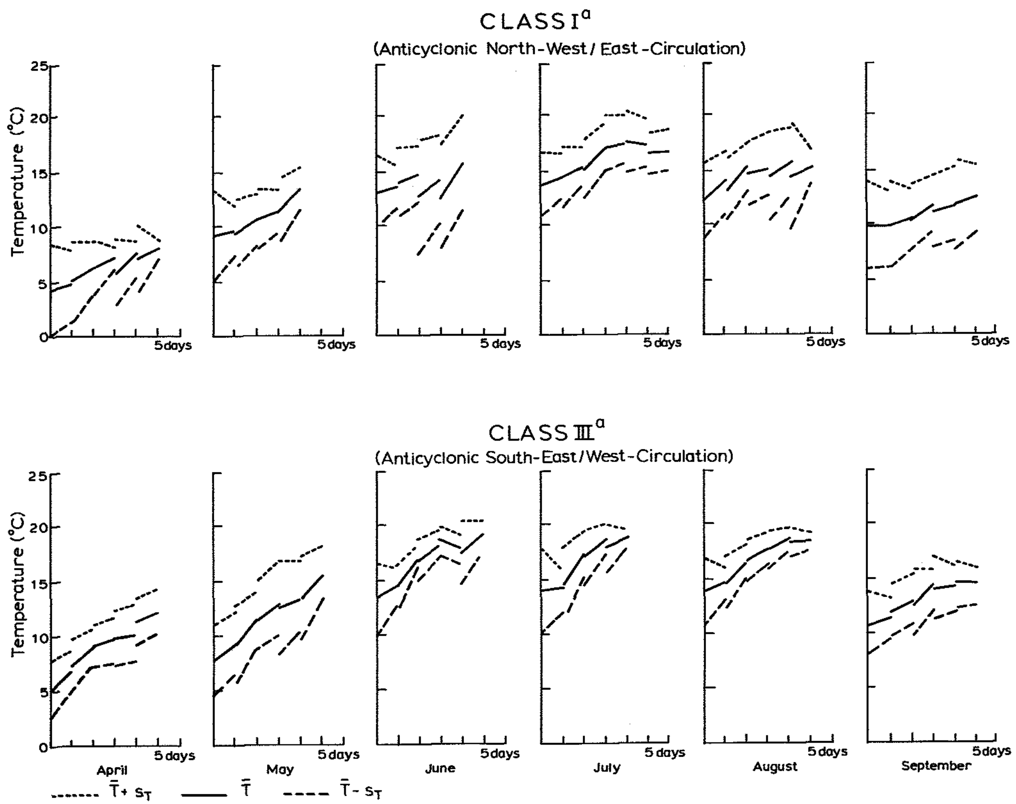


Fig. 3.8 The average course of temperature at Antholz (1236 m a.s.l., 1953-1975) during five successive days at three levels

antecedent conditions. The antecedent conditions which control the hydrologic processes are to a large extent governed by the impact of preceding weather types. Class III-a is preceded by cyclonic classes in 48.2% of the cases and by indifferent classes in 37.8% of the cases (table 2.6). During cyclonic and, to a lesser extent, during indifferent circulation, the melting process is tempered, the soil moisture and ground water systems are recharged and the pluvial-runoff system is activated.

The initial decrease of runoff during anticyclonic circulation is therefore explained by the decrease in delayed-runoff originating from the storage of the pluvial-runoff system.

The nival system, active during anticyclonic circulation, is initially still too weak to generate enough meltwater to compensate for the decrease of delayed-runoff. Only when initial runoff is relatively low, at the $\bar{q} - s_q$ level, the nival system is able to generate enough meltwater to increase river runoff at the start of the weather class.

$1^{st} \rightarrow 2^{nd}$ day: Continuation of the above described processes.

$2^{nd} \rightarrow 3^{rd}$ day: From the 2^{nd} to the 3^{rd} day we are confronted with a turning point in the average course of runoff. This turning point, which is most clearly expressed in the figure of July, points to the change of contributing systems. The delayed-runoff of the pluvial system still continues to decrease, but the nival system generates enough meltwater to increase river runoff at all three levels.

$3^{rd} \rightarrow$ ....: During the 3^{rd} and following days the nival (and glacial) system will tend to create a stable level runoff until the melting process is again interrupted by the succeeding class of weather types.

The difference in effect between the anticyclonic NW/E-circulation (class I-a) and anticyclonic SE/W-circulation (class III-a), which appeared very clearly from the mean day-to-day changes (fig. 3.5), is also demonstrated quite distinctly by this trend analysis. Although the above described mechanism also occurs in principle during anticyclonic NW/E-circulation (for ex. in May and July), the effect of the melt generating process is much smaller compared with anticyclonic SE/W-circulation. During August, class I-a shows a continuous decrease at all 3 levels while class III-a still shows an increase after 3 days.

Application of the above analysis to the indifferent and cyclonic classes showed that no systematic day-to-day course exists during those weather types as for the anticyclonic classes. This is mainly caused by the capricious, less systematic course of precipitation and by the fast reaction of the pluvial system to precipitation.

4 CONCLUSIONS

On the basis of the above analysis the following conclusions are drawn:

- The large differences in mean daily precipitation and mean daily temperature between the different classes as shown in fig. 3.1 and fig. 3.2 are much less pronounced in the mean runoff curves of fig. 3.3. This feature can be explained by a number of factors which are related to the complex character and variability of Alpine hydrologic systems, both in space (hypsometric features) and in time (seasonal- and year-to-year changes) on the one hand, and by the succession of weather types on the other. These main factors are:
  - The distinguished hydrologic sub-systems bring about an attenuation and a translation of the input from snow- and glacier-melt and precipitation, such that the runoff depends on the preceding runoff according to the characteristic times of the systems (autocorrelation). The dependence on preceding runoff appears very clearly from the mean day-to-day discharge changes (fig. 3.5) in combination with the mean daily runoff (fig. 3.3).
  - The antecedent hydrologic conditions are subject to large year-to-year changes, especially during the months with snow- and glacier-melt. Differences in snow-cover extent and physical characteristics (albedo, snow density, condition of ripening etc.) cause large variations in discharge which, in combination with the above mentioned autocorrelation, blur the distinctive mean runoff.
  - Anticyclonic SE/W-circulation (III-a) and cyclonic SE/NW-circulation (II-c and III-c) have the same influence on runoff during the melting season in nivo-glacial discharge areas, in the sense that they are both associated with increasing runoff (fig. 3.5), since anticyclonic weather types increase snowmelt-runoff and cyclonic weather types increase runoff from precipitation.

2. From the comparison of statistical phenomena of runoff such as the mean day-to-day changes (fig. 3.5) and the coefficient of variation (fig. 3.4) it may be concluded that the character of runoff during the different classes is different.

3. The magnitude of runoff during a particular weather type is to a large degree governed by:

   a) autocorrelation, related to the characteristic times of the active systems during the preceding weather types, and

   b) by antecedent conditions, probably mainly related to the extent and physical properties of the snow-cover.

4. Therefore, in order to describe the response of the catchment in relation to different weather types, it is necessary

   a) to have knowledge relating to the characteristic times of the sub-systems, and

   b) to define a measure (or measures) which incorporate antecedent conditions.

CHAPTER IV

WEATHER-TYPE RUNOFF FORECASTING MODEL

(W T R F)

INTRODUCTION

1.1 Some Remarks on Runoff Forecasting

Runoff forecasting involves the prediction of runoff phenomena, based either on a knowledge of underlying physical laws and physiographic influences of the catchment, or on statistical evidence. In the present context it refers to the prediction of runoff events in a deterministic sense, i.e., with emphasis on magnitude and actual time of occurrence as opposed to prediction in a probabilistic sense in terms of probability of occurrence (Yevjevich, 1978) or in a stochastic sense with emphasis on the probability of sequences of events (Shen, 1976; CSU, 1978).

The various aspects to runoff forecasting have been described with respect to theoretical principles (Ubell, 1966; Apollov et al., 1970; Němec, 1973; Mendel, 1974) and with respect to practical applications by operational methods (WMO, 1975a, 1975b, Mendel, 1976). Operational methods have been classified according to different premises such as the type of model used, the kind of input data, output data and the forecast period (WMO, 1975a; Mendel, 1978). With respect to the forecast period WMO (1975a) distinguishes between short-, medium- and long-range forecasting, where short-range covers several days, medium-range one or a few weeks and long-range from one to six months. This distinction is also used here.

In order to indicate the role of forecast weather-elements in runoff forecasting, the following rough division is made, according to basic input data:

A) Methods which use hydrometeorological observations in the catchment as basic data for the prediction of catchment response.

B) Methods which use observed stages and discharges as basic data either to predict the propagation of flood waves by flood-routing, or to predict river stages by statistical methods.

C) Methods which use information on preceding atmospheric circulation, which largely controls the distribution of temperature and precipitation.

D) Methods which use short-term weather predictions and initial catchment conditions to predict catchment runoff.

The use of short-term weather prediction in runoff forecasting (D) seems obvious since hydrological processes are primarily influenced by meteorological factors. However, as a result of storage-effects and travel time, their impact does not immediately result in a runoff reaction. As such, the response lags behind the meteorological processes. This offers the possibility of estimating future runoff phenomena without reference to future weather conditions (A,B,C). The lag-spectrum of the catchment dictates the lengths of the forecast periods, which in turn generally increase with the area contributing to runoff.

Ad A: For smaller catchments this lag-spectrum is governed by processes active during the transportation of water to a drainage channel and subsequently to the outlet, and catchment response can be described by Unit-Hydrograph methods such as performed by Mendel (1968), or by conceptual models which may contain a storage component. The latter are usually represented by a series of linear storages (storage approach) and a translation component, represented by time-area or isochrone methods (translation approach). An overview of such methods used for the description of catchment response can be found in Van de Griend (1980). For further comments on conceptual models see Dooge (1977) and the WMO-Project on Conceptual Models (WMO, 1975b, 1977).
Precipitation/snowmelt-runoff models used for smaller catchments have observed rainfall and/or snowmelt intensities as input data. An index for antecedent conditions may also be used to estimate the retention capacity of the catchment.

Ad B: In larger catchments and drainage basins with extended river systems, hydraulic processes and storage effects in the channels may be responsible for much larger lags (Mendel, 1973, 1974), and runoff models applied here usually comprise a flood-routing component. The Muskingum method, described by Linsley et al. (1958) and the Kalinin-Miljukow method (Kalinin & Miljukow, 1958; Apollov et al., 1970), both based on empirical relationships, are the most frequently applied in such circumstances. Hydraulic flood-routing methods are based on differential equations of unsteady flow (St. Venant) which describe the propagation of flood waves in river beds (see Gallati & Maione, 1977; Greco & Pannatoni, 1977). Input data consist of upstream discharges and known storage features of the channels to be passed through.
Extremely large lags such as long-term persistence phenomena from the river Rhine also occur (Wemelsfelder, 1960a, 1960b, 1963) and are related to long-term phase shifts between meteorological factors and recharge of soil moisture and groundwater feeding base-flow. Long-term runoff prediction over several months is thus performed on a statistical basis. The model uses observed long-term preceding river stages as input data.

Ad C: Probably the best examples of methods based on known relations between general characteristics of atmospheric circulation are reported by Apollov et al. (1970) with respect to the forecasting of ice break-up in rivers in the U.S.S.R. Using synoptical maps, Vangenheim (1940) established a statistical relationship between prevailing circulation types in winter and the time of ice break-up during the next spring.

The question of predicting runoff from small catchments over a period exceeding their natural lag encounters two problems, i.e., (1) the description of the catchment-response function mentioned under A and (2) the prediction of the future meteorological factors which govern the input to the catchment mentioned under D. As soon as future catchment response can be predicted on the basis of forecast weather elements, the prediction of runoff for larger catchments evolves from appropriate application of the flood-routing techniques mentioned under B. The complexity of hydrologic processes and the difficulty of obtaining accurate detailed hydrological and meteorological data both create problems with the description of response functions. In many cases the difficulty of forecasting accurate meteorological data is the main reason why runoff cannot be forecast with high precision on medium- and long-term. Knowledge of future weather conditions obviously plays a crucial part for increasing both accuracy and the period of runoff forecasting. At this moment accurate methods for quantitative prediction of weather elements on the medium- and long-term scale do not exist. Therefore, the possibilities of runoff forecasting are restricted by the degree to which future meteorological factors influence runoff and thus depend on the time lag between hydrological response and the corresponding meteorological influences.

1.2 The Use of Weather-Types in Runoff Forecasting

To a great extent atmospheric circulation controls the catchment input in terms of rainfall, temperature, radiation and other meteorological elements and thus atmospheric circulation can be regarded as the driving force behind all hydrologic processes. Therefore, it is to be expected that runoff phenomena of a particular catchment are related to occurring weather-types, especially on the medium-term. This would offer the possibility of applying forecast weather-charts directly to runoff forecasting. Such direct application of forecast weather-charts of atmospheric circulation to hydrologic forecasting, which forms the basis of the current approach, has not yet been found in the literature.

Accurate prediction of precipitation and temperature cannot be performed on the basis of known future weather-types (chapter II). The development of future weather, predicted and described in terms of weather-types consequently does not present more than an outline of the general character. The prognostic value of weather-types is thus limited to giving only a rough idea about future runoff.

For the river Ahr catchment, the study-area under concern, the lag between input and output is less than one day for both runoff from precipitation and from snow- and glacier-melt. For this catchment therefore, as for most catchments with comparable areal extent, the period of runoff forecasting is primarily restricted by the period for which weather-types can be forecast.*

Since the succession of one class of hydrologically relevant weather-types by other classes appeared to be almost random for this part of Europe (see chapter II, section 5), its application to short- and medium term weather-type forecasting is out of the question. For the development of the circulation on short- and medium term, the initial spatial distribution of barometric pressure and physical conditions of the atmosphere form the main determining factors. In fact, the pattern of barometric pressure forms the basis for the description and classification of daily weather-types according to Schüepp (1968) and large-scale weather-types according to Hess & Brezowsky (1959), but does not appear in numerical form in the actual weather-type descriptions.** Weather-types themselves do not, therefore, form a starting point for weather-type prediction.

In addition to the necessity of knowing the above mentioned physical conditions for weather-type forecasting, a thorough knowledge of the dynamics of air movement is necessary. This obviously belongs to the domain of synoptic and dynamic meteorology. For hydrological forecasting, this stresses the

* *Methods here are exclusively based on the relation between occurring weather-types and their directly related influences on hydrologic response. Other methods, such as those for long-term runoff prediction based on statistical relationships between wintery snow-fall and spring-runoff, for example, are not considered (for an overview of such methods see for ex.: WMO, 1970).*

** *Classifications in which the distribution of barometric pressure in numerical form is an essential property of the weather-type description are for ex. those proposed by Kirchhofer (1976) and Kruizinga (1978), and are known as objective classifications.*

necessity to combine both disciplines. That is hydrology on the one hand and meteorology on the other, where each is primarily concentrated on its own domain but where both should be directed to the same object: i.e., the combination of synoptic meteorology and hydrology into a "WEATHER-TYPE HYDROLOGICAL APPROACH". Within this allocation of tasks the field of activities of the hydrologist may well include the investigation of hydrological behaviour during different circulation types in relation to preceding or antecedent conditions. A first impulse to that aim is presented in this thesis. In forecasting hydrological processes according to this approach, the hydrologist is dependent on forecast weather charts and the length of the forecast. Clearly, the task of meteorology lies in the improvement of weather chart forecasting and on extension of the forecast period.*

During the last few decades great progress has been made in the prediction of air circulation several days in advance by means of multi-layer numerical models (see for ex. Kletter, 1957; Manabe et al., 1965; Arpe et al., 1976). For western-Europe, prediction of the 1000 mb and 500 mb charts ten days in advance is the aim of the "European Centre for Medium Range Weather Forecast (ECMWF)", in Reading, England (see: annual reports of the ECMWF). For the time being we will be confined to this 10-day weather chart forecast. The weather-type runoff forecasting model described below has thus been elaborated and tested with emphasis on this 10-day period.

2 CONCEPT OF WTRF-MODEL

2.1 Systems Approach

As in all physically oriented process-describing sciences, including hydrology, the model-concept cannot be ignored in either the deterministic or the statistical approach. All methods for describing input-output relations of hydrologic systems are based on MODELS developed from fictitious or experimental abstractions of nature. The degree to which the physical background forms a basis for the description determines its character and varies from the purely "black-box", via the "grey-box" to the "white-box" model.

* *Analogous to the existing weather-type classification systems developed initially as a framework for studying synoptic climatology (see chapter II, section 1), one could equally think of the systematic development of a HYDROLOGY-ORIENTED WEATHER-TYPE CLASSIFICATION in which meteorology should also play a crucial role.*

While physical-deterministic models use the mathematical formulation of physical laws which govern the hydrologic processes, statistical models on the other hand focus on the causal relation between assumed independent variables (predictors) and the system response, and have a statistical rather than a deterministic character. A variety of models exist nowadays for the description of catchment runoff which results from both precipitation (Sokolov et al., 1976; WMO, 1967, 1975a, 1975b, 1977) and from snowmelt (Martinec, 1960, 1965, 1970, 1976; Rantz, 1964, 1973; IASH, 1972; Herrmann, 1974; Obled & Rosse, 1977). Some of these have evolved pragmatically in response to practical situations, while others were developed within the framework of research projects. Their character therefore may vary significantly, mainly as a result of the different ways in which the catchment has been approached as a system and as a result of the different objectives for which the models have been designed. The description of runoff resulting from the combined effect of rainfall and snowmelt is still problematical because of the complexity of physical processes and is described by Hoeck (1952) and the U.S. Army Corps of Engineers (1956). An intercomparison of models for snowmelt runoff forecasting has recently been proposed by WMO (1979) with emphasis laid on the capability of computing both snowmelt- and rainfall-runoff. All the models selected for intercomparison have a physical-deterministic character, and thus they all assume detailed knowledge of the areal and time dependent initial factors as well as a known time-dependent system operation. However, publication of the final general report on the project results is not anticipated before the end of 1982.

When regarding the river Ahr catchment as a system in a deterministic sense, with emphasis on the functional relation between input governing factors related to the different circulation types as concluded from the analyses in chapter III, a fair knowledge of the characteristic times of the distinguished subsystems as well as of the respective initial conditions is a precondition. The estimation of these characteristic times from complex hydrographs composed of runoff from snow- and glacier-melt, direct runoff from precipitation and delayed groundwater runoff is extremely difficult, because:

- the characteristic times are usually not constant but may vary as a function of the partial runoff from the subsystems concerned. (Jacquet, 1960; Hall, 1968; Holtan et al., 1975; Brutsaert and Nieber, 1977).

- the hydrological subsystems all have an extremely variable character both in space, as a result of altitude and exposure influences, as well as in time due to seasonal influences (see chapter III).

Most of the existing models described in the literature (referred above) are based on known relations between catchment response functions and catchment conditions, and assume detailed information on initial conditions concerning physical snow characteristics, areal extension, snow depth, water-equivalent etc., which are only available for some specially instrumented and carefully selected experimental catchments (WMO, 1979). Such data are not available from the Ahr catchment.
Still, as it appeared from the analyses in chapter III, the antecedent conditions, especially those related to the snow-cover, are too much an influence on catchment response to be neglected. These antecedent conditions therefore, are represented by one single snowmelt-index I_s, to be estimated integrally from meteorological and runoff observations during the period preceding the forecast.

For the approach under consideration use is made of a statistical model in which input determining factors translated from the weather-types, conditional factors estimated from preceding meteorological observations and the snowmelt-index are related to future runoff.

2.2 The Regression Model

Notwithstanding the fact that the foundations of modern mathematical statistics have already been laid down at the beginning of this century, practical application has not been fully utilized until the rise and development of the computer. Full utilization of mathematical statistics in hydrology has been enhanced by the availability of long records of hydrologic and meteorologic data, eminently suitable for statistical treatment.

One of the best known statistical methods for the prediction of hydrological variables is the linear regression model which assumes the prediction of the dependent variable Y by means of a linear function of the independent variables X_i $(i=1,\ldots,n)$, such that

$$Y = a_o + a_1 X_1 + a_2 X_2 + \, . \, . + a_n X_n, \tag{4.1}$$

where a_i are the unknown regression coefficients to be estimated from observed values of X_i.

Table 4.1 Summary of dependent and a priori defined independent variables, selected for application in multiple linear regression and factor analysis

Variable X_i	Identification	Dimension	Description			
i=1	API	mm	Antecedent Precipitation Index		INITIAL VARIABLES	INDEPENDENT VARIABLES
2	ATI	^{o}C	Antecedent Temperature Index			
3	I_s	mm/^{o}C/day	Snow-cover Index			
4	Q_o	mm	Runoff during day of forecast			
5	Q_{-10}	mm/day	Runoff during 10 days preceding the forecast			
6	ΔQ	mm	Persistence factor			
7	I_T	^{o}C	Mean future 10-day temperature index	TRANSLATION-METHOD	FUTURE VARIABLES	
8	hI_T	^{o}C	Highest future 10-day temperature index			
9	lI_T	^{o}C	Lowest future 10-day temperature index			
10	I_P	mm/day	Mean future 10-day precipitation index			
11	hI_P	mm/day	Highest future 10-day precipitation index			
12	lI_P	mm/day	Lowest future 10-day precipitation index			
13	$I_s \cdot I_T$	mm/day				
14	$I_s \cdot hI_T$	mm/day				
15	$I_s \cdot lI_T$	mm/day				
16	RT_{10}	geop.dam - 500	Mean future 10-day relative topography	DIRECT-METHOD		
17	hRT_{10}	geop.dam - 500	Highest future 10-day relative topography			
18	lRT_{10}	geop.dam - 500	Lowest future 10-day relative topography			
19	AT_{500}	geop.dam - 500	Mean future 10-day 500 mb-level			
20	AT_{1000}	geop.dam	Mean future 10-day 1000 mb-level			
21	hAT_{1000}	geop.dam	Highest future 10-day 1000 mb-level			
22	lAT_{1000}	geop.dam	Lowest future 10-day 1000 mb-level			
23	$I_s \cdot RT_{10}$					
24	$I_s \cdot hRT_{10}$					
25	$I_s \cdot lRT_{10}$					
26	Q_{10}	mm/day	Mean future 10-day runoff			DEPENDENT VARIABLES
27	hQ_{10}	mm	Highest future 10-day daily runoff			
28	lQ_{10}	mm	Lowest future 10-day daily runoff			
29	Pr_{10}	mm/day	Mean future 10-day precipitation		OBSERVED FUTURE VARIABLES	
30	Tm_{10}	^{o}C	Mean future 10-day maximum temperature			

Theoretical background, computational methods used and application of significance tests are discussed in detail in Appendix A.

One of the major problems in regression analysis is how to select predictors before hand, i.e., variables which are expected to explain at least part of the variation of the dependent variable. This *a priori* selection should therefore necessarily be based on logical arguments and theoretical considerations, preferably supported from practical evidence. It consequently implies that the number of *a priori* selected variables exceeds the final number of predictors incorporated in the regression model. Since there are already powerful statistical methods to examine mutual dependency of variables within a multi-variate population (factor analysis, cluster analysis, partial-correlation analysis, step-wise regression analysis, etc.), it is better to incorporate a variable in the *a priori* selection than to neglect it, even if knowledge about its operation is limited.

At present the multiple regression model is also widely applied in non-linear form for short-, medium- and long-range runoff forecasting (Bidwell, 1971; Kilmartin, 1972) as well as for runoff from glaciers (Lugiez et al., 1969; Logan, 1972; Jensen & Lang, 1972). Daily short-range forecasts of the river Rhine (station Kaub) are performed routinely by the "Bundesanstalt für Gewasserkunde" (Teuber, 1970; Mendel, 1972, 1978), while a combined short-, medium- and long-range forecasting model has been developed by the ETH-Zurich for the station Rheinfelden. All are based on the (non-) linear regression model.

2.3 Model Variables

A. Dependent Variables

Since the prognostic values of the weather-types is limited to providing only a rough idea about future runoff, initial emphasis is laid on the prediction of mean runoff during the coming 10-day period, in correspondence with the 10-day medium-range forecast of weather charts aimed at by the above mentioned ECMWF. In addition, the highest and lowest daily runoff were also chosen to be predicted. This therefore produces the following dependent variables (variable identification numbers correspond to that given in table 4.1):

26) *Mean daily runoff during the coming 10-day period* (Q_{10})
27) *Highest daily runoff during the coming 10-day period* (hQ_{10})

28) *Lowest daily runoff during the coming 10-day period* (lQ_{10})

B. Independent Variables

All basic factors which govern the runoff process and form the basis for the current model can be subdivided into the following groups (see table 4.1):

a) INITIAL VARIABLES, which govern conditions at the time of forecasting and which in principle can be calculated or estimated on the basis of current hydro-meteorological observations or measurements. They are primarily related to catchment conditions.

b) FUTURE VARIABLES, which influence hydrological processes after the forecast has been issued. These variables, which include future weather conditions, can only be taken into account for the period in which forecast weather charts are available.

INITIAL VARIABLES

Initial conditions (also referred to as antecedent conditions), in principle show both temporal and spatial variations and are known to belong to the major influences responsible for the variation of the catchment system-operation (see chapter III). In order to incorporate the influence of initial conditions on the catchment system-operation generating runoff, several variables have been selected and are explained below.

1) *Antecedent Precipitation Index* (API)

Probably the best known index of initial moisture conditions within a drainage basin is the antecedent precipitation index and is a measure calculated from the sequence of preceding rainfalls. The most common form of API assumes that the impact of rainfall on basin storage and soil moisture decreases over time according to an exponential decay

$$API = \sum_{t=1}^{n} P_t K^t \qquad (4.2)$$

where, P_t = precipitation (mm) on a day t before the calculation date
K = a dimensionless constant

Values for the constant K are usually assumed to be in the range of 0.80 to 0.98, but the choice of the constant is usually not critical, especially when a non-linear relation between API and runoff is assumed as in coaxial graphical analysis (Becker, 1966a, 1968) since the API is only used as an index to moisture conditions. In the present study the K-value is set to 0.9, which means that the contribution of daily rainfall to the value of API is reduced to 50% in 6.5 days.

2) *Antecedent Temperature Index* (ATI)

In snow-covered areas the stage of snowpack ripening (see chapter I) is very important for the creation of snowmelt to be drained from the snowpack and contributed to runoff. After a very detailed investigation of meteorological influences on snowmelt runoff, Hoeck (1952) found that only after the retention capacity of the snowpack had been reached, did there exist a linear relation on a daily basis between energy available for snowmelt and actual snowmelt drainage from the snowpack. Therefore, the sequence of preceding temperatures (called Antecedent Temperature Index) is assumed to be a measure of the snow conditions. The influence of temperature is also assumed here to decrease over time as an exponential decay according to

$$ATI = \sum_{t=1}^{n} T_t \, K^t \tag{4.3}$$

where, T_t = mean temperature (°C) on a day t before the calculation date
K = a dimensionless constant

The value of K has been arbitrarily set to 0.8, which means that the contribution of temperature to the value of ATI is reduced to 50% in 3 days*.

3) *Snow Cover Index* (I_s)

The most important initial factors involved in snowmelt runoff are related to snow conditions and comprise a long series of factors such as extent of snow-cover, altitude of the snow-line, snow-depth, water content, snow structure, ripening condition, condition of the sub-soil, albedo etc., all factors which usually show variations both in time and in space. An excellent treatment of the subject is found in the summary report of the cooperative snow investigations by the U.S. Army Corps of Engineers (1956) and in a condensed version of that report by the same agency (1960).

* *A totally different application of ATI has been performed by Hopkins & Hackett (1961), as reported by Chow (1964, pg. 14-6) using the parameter to predict runoff from storm rainfall.*

Sufficient data on the above factors are not available for the Ahr valley. Even adequate information on snow-cover and snow-depth is lacking for the period of investigation, since the highest snow-depth measuring station is situated at an altitude of 1600 m and is already free of snow in the first half of March on average (see fig. 1.6).*

To overcome difficulties which accompany the computation of snow- and glacier-melt on the basis of theoretical concepts, arising from the wide variations in the above mentioned factors, the degree-day factor is widely used (see for ex. Martinec, 1960, 1965; Garstka, 1964; WMO, 1975). A degree-day is defined as a departure of 1 °C in mean daily temperature above 0 °C. The degree-day factor, which is considered an index of the integrated effect of radiation and sensible heat exchange, is defined as the depth of water melting from the snowpack in mm per degree-day. A weakness of the method lies in the fact that temperature cannot be regarded as an index for other meteorological factors such as radiation, wind speed and humidity. Furthermore, probably the main weakness lies in the fact that the degree-day factor depends on the above mentioned snow-conditions which also change continuously as the season progresses. This explains the great variation of values for the degree-day factor found in the literature even for the same basins during the melting season as found by Rantz (1964). Application of the degree-day method is therefore expected to lead to unsatisfactory results unless the factor-value is known for different conditions of the snowpack, as shown by Rantz (1973), or the factor-value can be estimated for the specific basin conditions at the date of forecast.

In order to satisfy the above arguments all initial conditions with respect to the snowpack and glaciers are condensed into one single index, denoted snow-cover index I_s, and defined as:

I_s = the amount of generated melt which can be drained freely from the snowpack per day and per degree of maximum daily temperature (°C) above a reference temperature, expressed in units of depth over the whole catchment.

* *Recent research has indicated that satellite-images provide practical means for the determination of areal extent of snowcover (Barnes et al., 1968, 1973; Itten, 1970; Haefner et al., 1974, 1980), glaciers (Muller et al., 1980) and even of snow-conditions (McGinnis, 1972; Meier, 1975). However, satellite-images have not been used for this investigation, primarily because the record of available images does not extend back far enough to cover the whole period of study.*

This snow-cover index can be estimated integrally from a 10-day period preceding the date of forecast by the general equation:

$$I_s = \frac{(Q_s)_{10}}{(Tm_{10} - t_c)} \tag{4.4}$$

where, $(Q_s)_{10}$ = 10-day average freely drainable snowmelt (mm/day)
Tm_{10} = 10-day average max. daily temperature (^{o}C)
t_c = temperature at which snowmelt starts (^{o}C)

The insertion of t_c permits adjustments for aspect, elevation, or other factors usually involved in relating snowmelt to temperature records and is particularly important when snowmelts at higher elevations are computed from temperatures observed at lower elevations - such as in our case at a fixed valley station. However, since data on snow-line elevation are not available, t_c has been set equal zero for convenience here.

The snowmelt component from the complex hydrograph, which is composed of nival, glacial and pluvial components, is estimated from the 10-day period water-balance preceding the date of forecast. Since storage changes in the catchment include changes in snow-mass and glacier ice (see chapter I), the water-balance has been restricted to the fluid cycle as follows:

$$\int Q_s\, dt = \int Q_t\, dt - \int P'\, dt + \int E'\, dt + \Delta S' \tag{4.5}$$

where, Q_s = melt component of runoff
Q_t = total runoff
P' = areal precipitation falling in fluid form (rainfall)
E' = part of P', which does not runoff eventually (evapotranspiration part of P')
$\Delta S'$ = change in directly drainable storages in the catchment during the balance period.

Areal Precipitation and Evapotranspiration

Areal precipitation is estimated from rainfall records at the stations St. Jakob, St.Johann and Rain, after correction for the depth-elevation distribution discussed in chapter I (fig. 1.18). However, the input of fluid precipitation (rainfall) may be overestimated, since during a considerable part of the year in the higher areas part of the precipitation is falling as snow and does not run off as a direct response; it will run off as snow-melt-runoff eventually. This explains the necessity to include only fluid precipitation in the water-balance equation.

That part of the total precipitation which either runs off during the balance period or is stored in directly drainable storage to appear as delayed runoff, equals

$$\int P' \, dt - \int E' \, dt \tag{4.6}$$

and can be written as a fraction of the total precipitation P by means of a reduction factor such as

$$R \int P \, dt \tag{4.7}$$

where, R = a reduction factor, giving the fraction of total precipitation that will either runoff directly or will be stored directly in fluid form to leave the catchment as delayed runoff.

Equation 4.5 then reduces to:

$$\int Q_s \, dt = \int Q_t \, dt - R \int P \, dt + \Delta S' \tag{4.8}$$

The Change in Directly Drainable Storage ($\Delta S'$)

The change in directly drainable storage $\Delta S'$ may in principle be separated into two components, i.e., (a) storage changes related to the nivo-glacial system and (b) storage changes related to the pluvial system. For a 10-day balance period these components may form a considerable item in the balance equation and they can only be estimated accurately if the system characteristics are known.

As a first approximation one can assume a fictitious reservoir where storage S is proportional to the outflow Q,

$$S = k.Q \tag{4.9}$$

where k is the storage coefficient with the dimension of time, also denoted characteristic time. This assumption is known as the "*linear reservoir concept*". If no inflow occurs to the reservoir then the equation of continuity becomes

$$\frac{dS}{dt} = -Q \qquad (4.10)$$

After differentiation of eq. 4.9 in combination with eq. 4.10, it follows that

$$k\frac{dQ}{dt} = -Q \qquad (4.11)$$

and using the boundary condition $Q = Q(0)$ when $t=0$, eq. 4.11 may be solved as a recession equation of exponential form

$$Q(t) = Q(0).e^{-\frac{1}{k}t} \qquad (4.12)$$

where, $Q(t)$ = runoff at time t
k = characteristic time of the linear storage
e = logarithmic base

The change in storage during the interval ($t \rightarrow t+\Delta t$) under recession flow follows directly from the linear assumption (eq. 4.9) and equals

$$\Delta S = k\left\{Q(t + \Delta t) - Q(t)\right\} \qquad (4.13)$$

In catchments where snow- or glacier-melt do not play a part, the storage-runoff relationship and corresponding characteristic times are easily found by plotting rainfall generated recession curves on to a semi-logarithmic scale. Several straight line segments may normally be discernible, which are usually ascribed to different contributing storages ranging from channel storage to deep groundwater storage (see for ex. Hall, 1968; Gregory & Walling, 1973; De Zeeuw, 1973; Holtan, 1975). Determination of the respective characteristic times is possible under the assumption that all distinguished storages are emptied in a fixed sequential order. This however, is not the case when the pluvial system and the nivo-glacial system are concurrently active in creating runoff in an almost mutually independent relation, and in this situation the determination of characteristic times by graphical procedures is impossible.

Application of the above linear-reservoir concept to both systems leads to the following recession equations:

$$Q_s(t) = Q_s(0).e^{-\frac{1}{k_s}t} \tag{4.14}$$

$$Q_r(t) = Q_r(0).e^{-\frac{1}{k_r}t} \tag{4.15}$$

where, $Q_s(t)$ = snowmelt runoff at time t

$Q_r(t)$ = rainfall generated runoff at time t

$Q_t(t)$ = $Q_s(t) + Q_r(t)$ *(total runoff)*

k_s, k_r = characteristic times of directly drainable fictitious linear storages

The change of directly drainable storage during the interval $(t \rightarrow t+\Delta t)$ is then estimated by integration of both equations and is given by:

$$\Delta S' = k_s\left\{Q_s(t + \Delta t) - Q_s(t)\right\} + k_r\left\{Q_r(t + \Delta t) - Q_r(t)\right\} \tag{4.16}$$

In order to estimate the values of k_s and k_r, assuming that both systems can be described according to the linear reservoir concept, a combined melt/rainfall-runoff model has been developed and is fully discussed in Apendix B. The basic equations are:

$$Q_s(t) = Q_s(t - \Delta t).e^{-\frac{1}{k_s}\Delta t} + I_s.Tm(t).(1 - e^{-\frac{1}{k_s}\Delta t}) \tag{4.17}$$

$$Q_r(t) = Q_r(t - \Delta t).e^{-\frac{1}{k_r}\Delta t} + R \cdot P(t).(1 - e^{-\frac{1}{k_r}\Delta t}) \tag{4.18}$$

where, $Q_s(t)$, $Q_r(t)$ = snowmelt runoff and rainfall runoff at day t

$P(t)$ = precipitation at day t

$Tm(t)$ = max. temperature at day t

I_s = snow-cover index (explained above)

R = precipitation reduction factor (explained above)

Δt = 1 day

(other variables as above)

In addition, an incremental delay ($\tau = 0, 1, \ldots, n$ days) has been introduced between daily runoff and daily mean temperature. Visual analyses indicated that the delay between rainfall and runoff is less than one day and has been taken zero.

It would also be more realistic here to insert a reference temperature t_c at which snowmelt starts. However, in our case, this means the introduction of another parameter which is dependent on I_s, which interferes with parameter optimization.

Estimation of parameters K_s, K_r, I_s and R, where $K_s = e^{-\frac{1}{k_s}\Delta t}$ and $K_r = e^{-\frac{1}{k_r}\Delta t}$, has been performed by a non-linear least squares technique for over-determined systems (see Kowalik & Osborne, 1968). The model has been applied to the analyses of the complex runoff-hydrographs for the river Ahr at Steinhaus for each month from May to September on the 22-year period (1953-1974) of available observations. The results have been summarized in table 4.2. The parameters show a notable variation, explained by a number of factors such as:

a) errors in the estimation of areal precipitation and temperature
b) the actual variation of the precipitation reduction factor R
c) assumption of the linear reservoir-concept (which violates reality), and
d) actual changes of system circumstances from one year to the next and also within each month.

Although these variations exist, the mean results for each month seem quite satisfactory to give an overall estimate. Mean K_s-values vary between 0.68 and 0.52, corresponding to 2.6 days and 1.5 days respectively. These values are much lower than that found by Martinec (1970) for the Dischma catchment in the eastern part of Switzerland. He reported K_s-values which vary between about 0.9 and 0.75, or 9.5 days and 3.5 days respectively. Martinec used a graphical method proposed by Langbein (1940), and plotted daily runoff values against that of the next day during recession flow. This in fact should not be applied as argued above, even when runoff from rainfall can be ignored, since snowmelt runoff is hardly ever in complete recession; the snowmelt system is continuously recharged even during the night-time.

From the values in table 4.3 it follows that the contribution of runoff from fluid precipitation (rainfall) is far less than the contribution from snow- and glacier-melt. Realising further that application of eq. 4.16 for

Table 4.2 SUMMARY OF RESULTS OF HYDROGRAPH-ANALYSES OF THE RIVER AHR, →

	RAINFALL-RUNOFF SYSTEM PARAMETERS							MELT-RUNOFF →		
Month	$\bar{K}_r$	$s_{(K_r)}$	k_r (days)	$\bar{R}$	s_R	$\frac{s_R}{\bar{R}}$	R^*	$\bar{K}_s$	$s_{(K_s)}$	k_s (days)
May	0.83	0.21	5.4	0.40	0.23	0.58	0.29	0.62	0.16	2.1
June	0.79	0.11	4.2	0.35	0.20	0.57	0.31	0.56	0.15	1.7
July	0.74	0.18	3.3	0.35	0.10	0.29	0.33	0.53	0.16	1.6
August	0.74	0.16	3.3	0.41	0.19	0.46	0.44	0.52	0.15	1.5
September	0.84	0.12	5.7	0.41	0.25	0.60	0.38	0.68	0.13	2.6

Explanation of symbols:

$\bar{K}_r$: Mean of recession coefficients (K_r) of rainfall-runoff system based on one-day time increment (Δt = 1 day)

$\bar{K}_s$: Mean of recession coefficients (K_s) of melt-runoff system based on one-day time increment (Δt = 1 day)

k_r : Estimated characteristic time of rainfall-runoff system ($k_r = -\frac{\Delta t}{\ln \bar{K}_r}$)

k_s : Estimated characteristic time of melt-runoff system ($k_s = -\frac{\Delta t}{\ln \bar{K}_s}$)

$s_{(\cdot)}$ = Standard deviation of $(\cdot)$

$\bar{R}$ = Mean of reduction coefficients of precipitation (R) found for the particular month and different years

R^* : Reduction coefficient, giving for the particular month over all years the fraction of total precipitation which left the catchment as runoff during the simulation periods, or which has been stored in *"directly drainable storages"*

$\bar{I}_s$: Mean of snow-cover index (I_s) giving the amount of melt per ^oC (mm/day)

– : Coefficient of correlation between computed and observed daily runoff

C_v : Coefficient of variation of residuals defined as:

$$C_v = \frac{\left\{\frac{\sum(Q_c - Q_o)^2}{n}\right\}^{\frac{1}{2}}}{\bar{Q}_o}$$

where: n = number of days per month

Q_c = computed daily runoff after optimization

Q_o = observed daily runoff

$\bar{C}_v$: Mean of C_v

N : Number of simulations with satisfactory results (some simulations resulted in negative runoff values of the system to start with and have been deleted)

FOR THE MONTHS MAY TO SEPTEMBER OVER THE PERIOD 1953-1974

SYSTEM PARAMETERS			Monthly mean values of runoff, precipitation and max. temperature			STATISTICS				
$\bar{I}_s$ (mm/day/°C)	$s_{(I_s)}$	$\frac{s_{(I_s)}}{\bar{I}_s}$	$\bar{Q}$ (mm/day)	$\bar{P}$ (mm/day)	$\overline{Tm}$ (°C)	$\bar{r}$	s_r	$\bar{C}_v$	$s_{(C_v)}$	N
0.27	0.09	0.33	4.62	2.37	15.3	0.86	0.07	0.25	0.05	17
0.41	0.13	0.31	8.25	3.40	18.2	0.88	0.07	0.13	0.03	15
0.31	0.10	0.32	7.77	3.99	21.0	0.83	0.13	0.12	0.03	17
0.22	0.07	0.32	6.58	3.89	21.3	0.88	0.06	0.14	0.02	15
0.14	0.04	0.29	3.84	2.20	17.8	0.85	0.08	0.16	0.03	14

Table 4.3

Month	$\bar{Q}$ (mm/day)	$\bar{P} \cdot R^*$ (mm/day)	$\frac{\bar{P} \cdot R^*}{\bar{Q}}$ (%)	$\overline{\Delta S}$ (mm/day)
May	4.62	0.69	15	+0.23
June	8.25	1.05	13	+0.21
July	7.77	1.32	17	+0.04
August	6.58	1.71	26	-0.10
September	3.84	0.84	22	-0.44

$\overline{\Delta S}$ = Mean monthly change in drainable storage expressed in mm/day

(other variables as defined in table 4.2) the estimation of $\Delta S'$ requires the knowledge of the partial contribution to runoff from both systems at the beginning and end of each 10-day balance period - which is practically impossible - $\Delta S'$ has been approximated using the value of k_s according to

$$\Delta S' = k_s \left\{ Q_t(e) - Q_t(b) \right\} \tag{4.19}$$

where, $Q_t(b)$, $Q_t(e)$ = total observed runoff at the beginning and end of the balance period respectively

Combination of eq. 4.4, eq. 4.8 and 4.19, with t_c=0, then leads to an estimate of I_s for each balance period according to:

$$I_s = \frac{1}{10} \left\{ \frac{\int_0^{10} Q_t(t)\, dt - R \int_0^{10} P(t)\, dt + k_s \left\{ Q_t(e) - Q_t(b) \right\}}{Tm_{10}} \right\} \tag{4.20}$$

4 and 5) *Autoregressive terms* (Q_o and Q_{-10})

The tendency of hydrological systems to attenuate input into the system and to translate it in time implies a dependency of runoff events on preceding ones, which may be applied for purposes of runoff forecasting. The accuracy and the forecast-period both progressively increase with increasing characteristic times of the systems involved. This dependency is usually denoted autocorrelation and plays a crucial part a.o. in stochastic analysis of time series (Shen, 1976) and stochastic models (Yevjevich, 1972) based thereupon.

In order to investigate how much this autocorrelation contributes to the variation of future 10-day mean runoff, the following two independent variables have been incorporated:

Q_o = runoff (mm) at the date of forecast
Q_{-10} = mean runoff (mm/day) during the preceding 10-day period, including the date of forecast

The Autoregressive Character of the Runoff Time Series

In order to evaluate beforehand the autoregressive character of the runoff time series, they have been subjected to time series analyses. Essentially three types of correlation functions should be distinguished. The first deals with the dependency WITHIN the series; the second deals with the dependency BETWEEN the series and a third concerning the OVERALL time dependency based on a sample of time series.

The seasonally dependent variable character of the nivo-glaciated catchment of the river Ahr restricts serial analysis to a reduced, say monthly, basis. This produces a sample of 22 independent series for each month over the period 1953-1974.

The Autocorrelation Function

Considering a time series as shown in fig. 4.1, the dependency between the values of x at time t and that at time $t+k$ can be described by the autocorrelation function, defined by Yevjevich (1972) as:

$$\rho_k = \frac{\gamma_{xx}(t,\ t+k)}{\tau_x(t) \cdot \tau_x(t+k)} \qquad (4.21)$$

where, ρ_k = autocorrelation coefficient for the lag k
γ_{xx} = autocovariance of x
$\tau_x(\cdot)$ = standard deviation of x

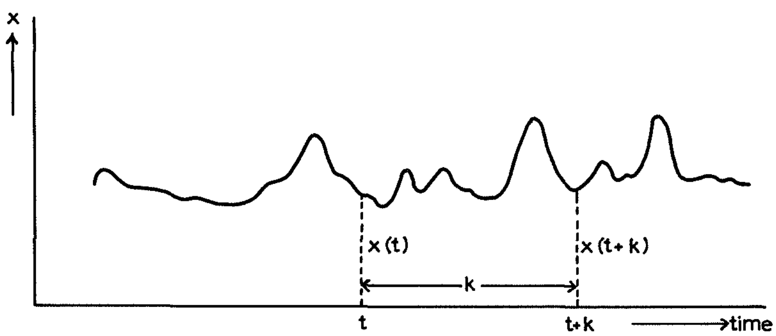


Fig. 4.1 Time series with values at times t and t+k

The function ρ_k is estimated from a sample of size N by (Yevjevich, 1972 p. 40):

$$r_k = \frac{\sum_{i=1}^{N-k} (x_i - \bar{x}).(x_{i+k} - \bar{x})}{\sum_{i=1}^{N} (x_i - \bar{x})^2} \tag{4.22}$$

with $\quad \bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i$

where r_k (k= 1,...,m) is the sample autocorrelation at time-lag k and m is the maximum number of lags to be computed, which should be in the order of at most N/3 (Yevjevich, 1972, p. 101). For daily runoff values on a monthly basis this leads to a maximum lag of 10 days. A plot of the autocorrelation function ρ_k versus lag-k is called a "correlogram" and indicates the autocorrelation structure of the time series. Examples of some typical correlograms are given in fig. 4.2.

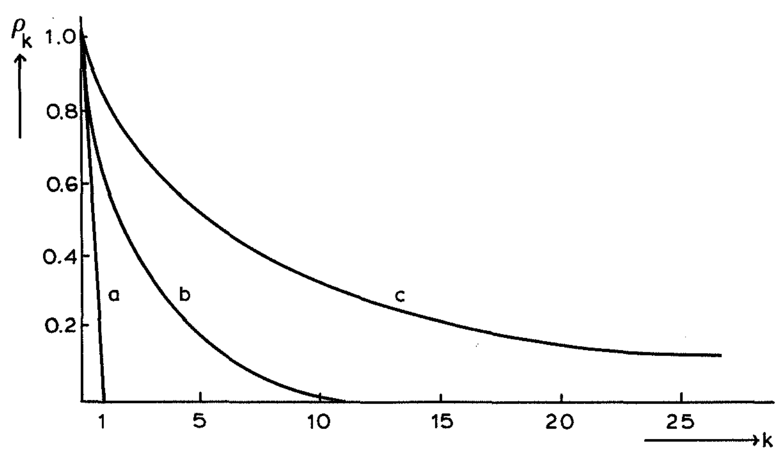


Fig. 4.2 Some typical correlograms of (a) time independent, (b) short-term dependent and (c) long-term dependent time series

Correlogram of r_k within the Series

In order to eliminate the variance between the monthly time series, all elements of the same monthly series have been reduced by their serial mean. Correlograms of r_k within the resulting time series are shown in fig. 4.3, and indicate a rather short-term dependency which corresponds with the low characteristics times found above, especially for July and August.

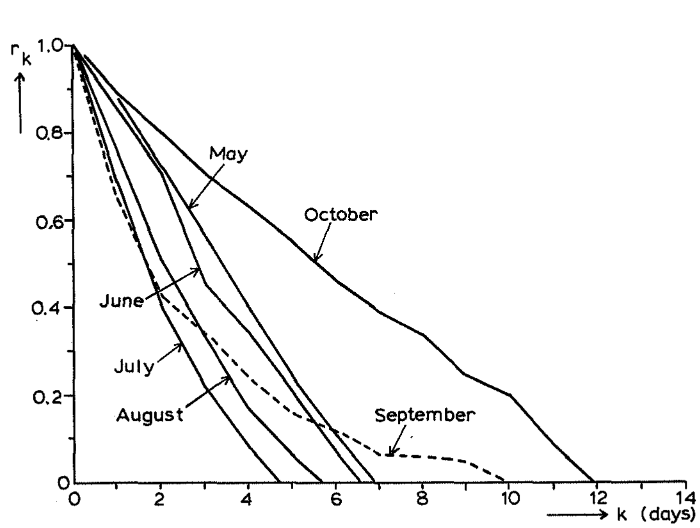


Fig. 4.3 Correlogram of r_k between discharge on day n and day n+k, within the samples of time series, of the river Ahr at Steinhaus, 1953-1975 (values of r_k are presented in table 4.4)

Correlogram of r_k based on a Sample of Independent Series

By comparison, the lag-k autocorrelation function of daily runoff values based on a sample of monthly series shows a distinct long-term dependency (fig. 4.4), which should be explained from the high external variance between the series as noted already in chapter III, rather than from the characteristic times of the hydrologic systems involved. This year to year variation of monthly mean runoff is governed by the variation in snow-cover, snow-conditions, albedo of the glacier surfaces etc., and applies to all except the winter months (see chapter III). It is responsible for the high values of r_k (fig. 4.4) and thus offers the possibility of incorporating an

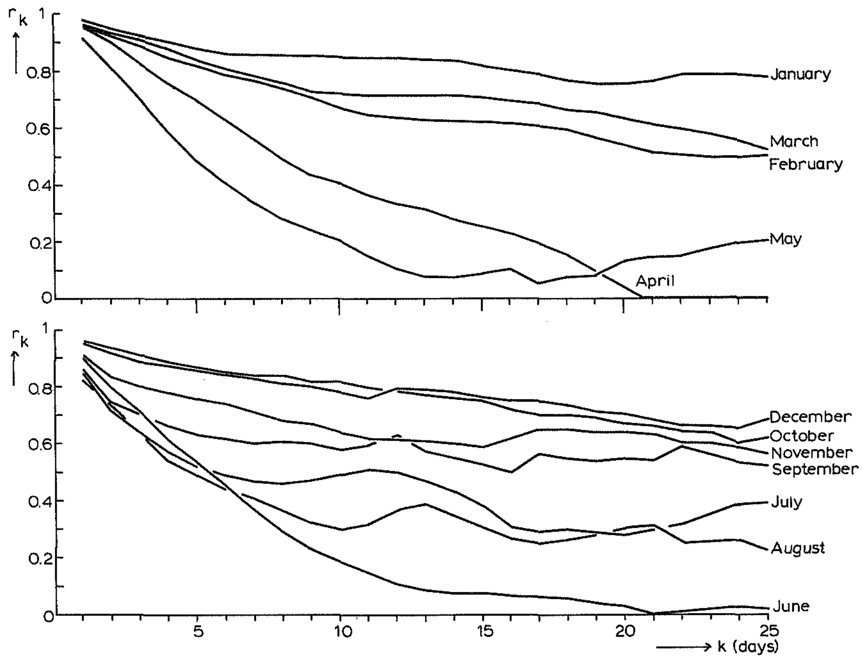


Fig. 4.4 Correlogram of r_k between discharge on day n and day n+k, based on samples of independent time series (overall autocorrelation) of the river Ahr at Steinhaus, 1953-1975 (values of r_k are presented in table 4.5)

autoregressive term in the prediction model. Finally, fig. 4.5 shows the correlogram of the overall autocorrelation function between runoff at day t, denoted $x(t)$, and mean runoff during the following k-day period, denoted $x_k(t)$, where

$$x_k(t) = \frac{1}{k} \sum_{i=1}^{k} x(t + i) \qquad (4.23)$$

The summary graph of fig. 4.6 shows for each month (a) the lag-10 overall autocorrelation, and (b) the overall autocorrelation between runoff at day t and mean runoff during the following 10-day period. The computed values of r_k are given in tables 4.4 up to 4.6.

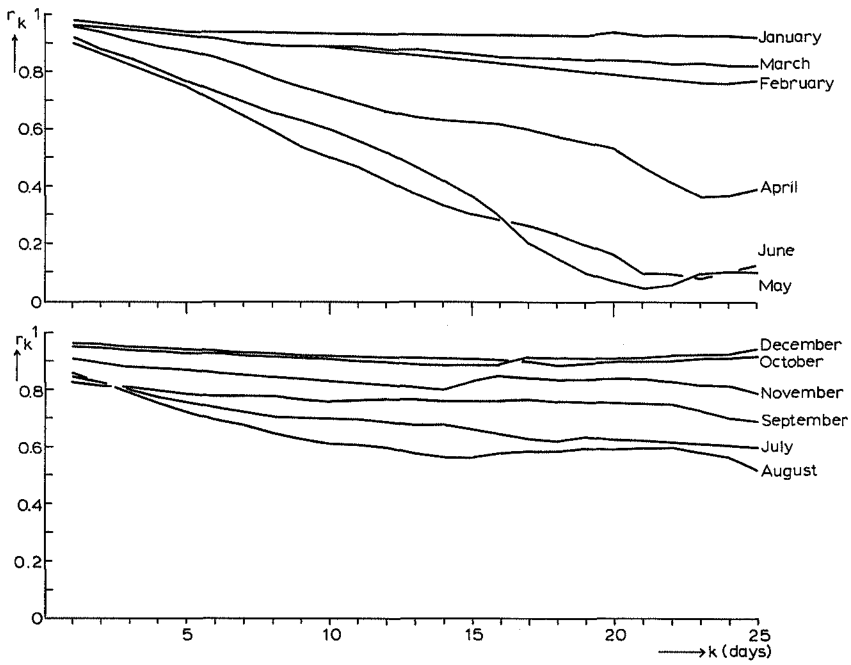


Fig. 4.5 Correlogram of r_k between discharge on day n and mean discharge during the next k days, based on samples of independent time series (overall autocorrelation) of the river Ahr at Steinhaus, for each month (1953-1975) (Values of r_k are presented in table 4.6)

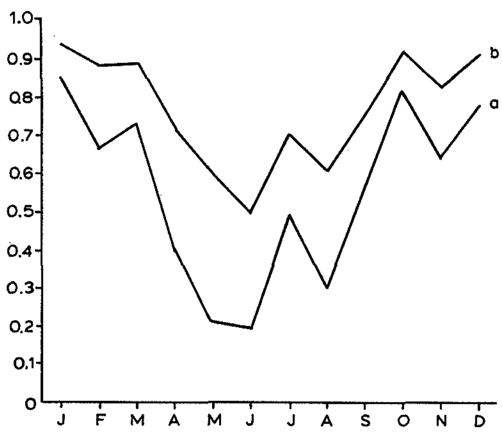


Fig. 4.6

a) Lag-10 overall autocorrelation between discharge on day n and day n+10, for each month

b) Lag-10 overall autocorrelation between discharge on day n and mean discharge during the next 10 days

(River Ahr at Steinhaus, period 1953-1975)

Table 4.4 Coefficients of correlation (%) between daily discharge on day n and day $n+k$ for each month within the samples. River Ahr at Steinhaus, 1953-1975.

k	J	F	M	A	M	J	J	A	S	O	N	D
1	88	87	88	94	89	85	69	75	65	89	73	84
2	73	75	75	81	72	71	40	51	42	80	50	70
3	59	60	65	67	56	45	22	33	36	71	40	59
4	45	42	53	54	40	34	8	17	24	63	33	50
5	28	29	39	40	24	21	-3	7	16	55	27	40
6	14	18	24	24	11	7	-10	-2	12	46	19	34
7	10	8	12	8	-1	-6	-15	-7	7	39	13	26
8	6	-2	0	-5	-11	-16	-14	-16	7	34	4	19
9	1	-5	-1	-8	-12	-8	-9	-9	5	25	-1	11
10	-2	-2	-5	-4	-6	-10	-6	-10	0	20	-5	4

Table 4.5 Coefficients of correlation (%) between daily discharge on day n and day $n+k$ for each month. River Ahr at Steinhaus, 1953-1975. (Overall autocorrelation, based on samples of independent time series)

k	J	F	M	A	M	J	J	A	S	O	N	D
1	98	96	96	96	92	90	85	86	83	96	91	96
2	95	93	93	90	81	80	72	73	73	94	83	92
3	93	89	91	83	70	70	64	63	71	91	80	89
4	91	85	88	76	59	61	57	54	66	89	78	88
5	88	82	84	70	49	54	52	49	63	87	76	86
6	86	79	81	63	41	46	49	44	62	85	74	85
7	86	77	78	56	34	37	47	41	60	84	71	83
8	86	74	76	49	28	29	46	36	61	84	68	81
9	86	71	73	44	24	23	47	32	60	82	67	80
10	85	67	73	41	21	19	49	30	58	82	64	78
11	85	65	72	37	15	15	51	32	59	80	62	76
12	85	64	72	34	11	11	50	37	63	78	62	79
13	84	63	72	32	8	9	47	39	57	77	61	79
14	84	63	72	29	8	8	43	35	55	76	60	78
15	82	63	71	26	9	8	38	30	53	75	59	76
16	81	62	70	24	11	7	31	27	50	72	62	75
17	79	61	69	20	6	7	29	25	56	70	65	75
18	77	60	67	16	8	6	30	26	55	70	65	73
19	76	57	66	10	9	4	29	28	54	69	64	71
20	76	54	64	4	14	3	28	30	55	67	64	70
21	77	52	62	-1	15	0	30	31	54	66	63	68
22	79	51	60	-6	15	1	32	25	59	64	60	66
23	79	50	57	-9	18	2	35	26	56	64	60	66
24	79	51	56	-9	20	3	39	26	53	60	59	65
25	78	51	52	-6	21	2	39	23	52	62	56	68

Table 4.6 Coefficients of correlation (%) between daily discharge on day n and mean daily discharge during the next k days. River Ahr at Steinhaus, 1953-1975. (Overall autocorrelation, based on samples of independent time series)

k	J	F	M	A	M	J	J	A	S	O	N	D
1	98	96	96	96	92	90	85	86	83	96	91	96
2	97	96	96	94	88	87	82	82	81	96	89	95
3	96	95	95	91	85	83	80	79	81	95	88	94
4	96	93	94	89	81	79	78	75	80	95	88	94
5	95	92	93	88	77	75	76	72	79	94	87	93
6	94	91	92	85	73	70	74	69	78	94	86	93
7	94	90	90	82	69	65	72	68	78	93	85	92
8	94	90	89	78	66	60	71	65	78	93	84	92
9	94	89	89	75	63	54	70	63	77	92	84	91
10	94	89	89	72	60	50	70	61	76	92	83	91
11	94	88	89	69	56	47	70	61	76	92	82	90
12	94	87	88	66	52	42	69	60	77	91	82	90
13	94	86	88	64	47	37	68	58	77	91	81	89
14	94	85	87	63	42	33	68	57	76	91	80	89
15	95	84	86	63	36	30	66	56	76	91	83	89
16	94	83	85	62	29	28	65	58	76	90	85	89
17	94	82	85	60	20	26	63	59	77	90	84	91
18	94	81	85	58	15	23	63	59	76	89	84	91
19	94	80	84	56	9	19	64	60	76	89	84	91
20	94	79	84	53	6	16	63	59	76	90	84	91
21	93	78	84	47	4	11	63	60	75	90	84	91
22	93	77	83	41	5	9	62	60	75	90	83	92
23	93	76	83	36	9	8	61	58	73	91	82	92
24	93	76	82	37	10	10	61	56	70	91	82	93
25	92	77	82	39	10	12	60	52	69	92	79	95

6) *Persistence* (ΔQ)

Since the autoregressive terms are to a large degree governed by the year to year variations of mean runoff they cannot be regarded as a measure of actual persistence of runoff. In order to represent possible persistence phenomena, the daily change in runoff during the day of forecast $Q(t)$ and the preceding day $Q(t-1)$ has been introduced as an additional persistence factor ΔQ, where

$$\Delta Q = Q(t) - Q(t-1) \tag{4.24}$$

FUTURE VARIABLES

In the present context, future variables refer to known future weather conditions and can only be accounted for over the period for which weather forecasts exist. All future variables applied here can be extracted from forecast weather charts. Two groups of factors are distinguished and are applied separately in order to compare their usefulness in runoff forecasting. These groups are (see also table 4.1):

A. Variables based on relations between meteorological factors and (classes of) weather-types, translated from forecast weather charts *(translation method)*. These factors will be discussed below.

B. Variables which can be directly derived from forecast 500- and 1000 mb charts, without the above translation *(direct method)*. These factors will be discussed separately in a subsequent section.

A. Variables determined by translation method

Future weather-types can be determined on the basis of 10-day forecast weather charts performed by the ECMWF. Since this present investigation concerns primarily the applicability of weather-types translated from forecast weather charts, the model has been tested on the basis of correctly forecast weather events. Although the accuracy of weather chart forecasting - primarily the concern of meteorologists - determines its ultimate applicability to runoff forecasting, both matters should be separated in the present context.

7) *Mean future 10-day temperature index* (I_T)

The impact of temperature during the coming 10-day period is estimated by given weather-types and monthly mean temperature departures from normal pentad values (ΔT). These temperature departures have been computed for the distinguished classes of weather-types for each month as presented in table 4.7 (see also fig. 4.7).

Because the normal cycle of runoff during the year is closely related to that of temperature and not to that of temperature departures (ΔT), the temperature departures were added to the normal pentad values of table 4.8.

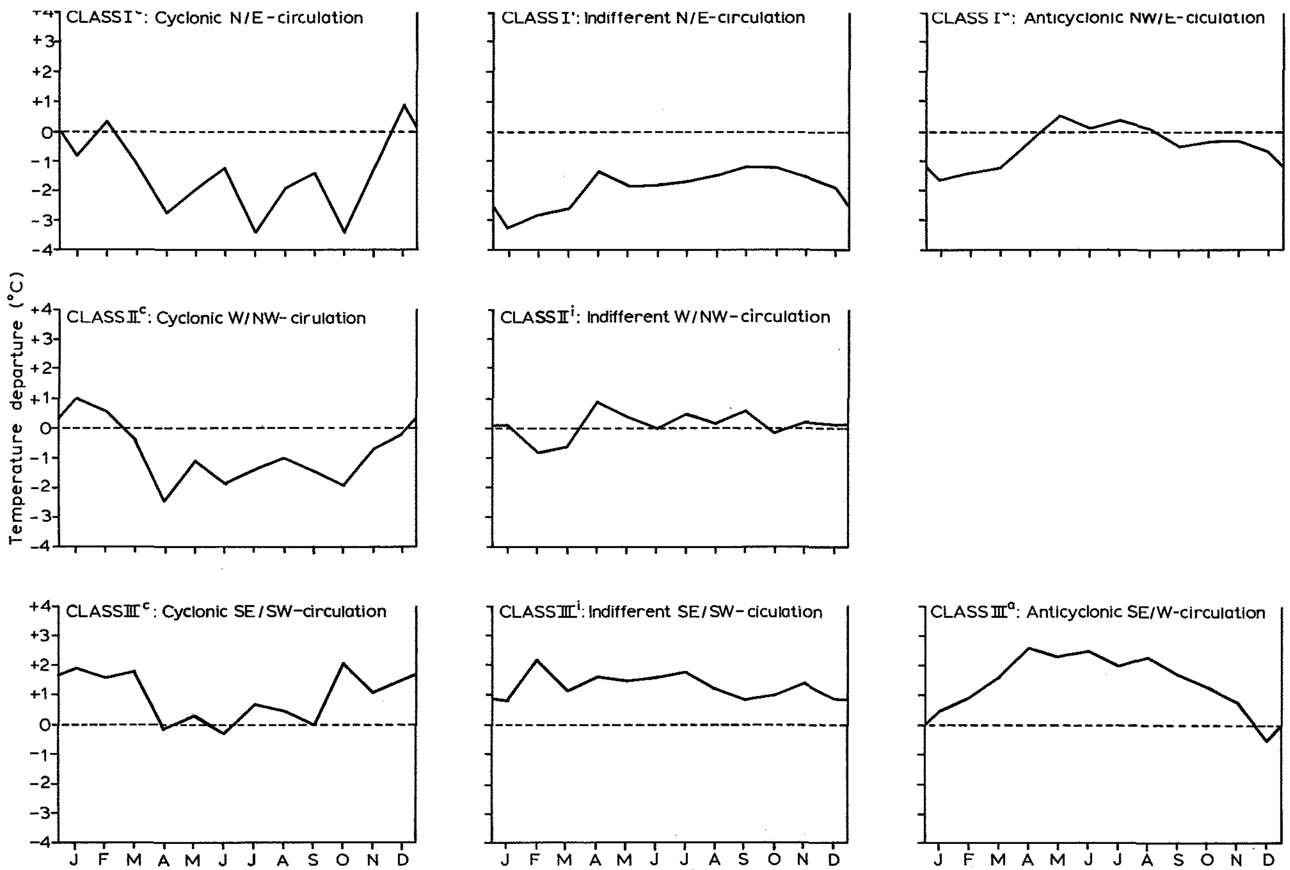


Fig. 4.7 Mean temperature departures (ΔT) from normal pentad values for the distinguished classes of weather-types and for different months

Table 4.7 Mean temperature departures (ΔT) from normal pentad values for the distinguished classes of weather-types and for different months (^{o}C).

	Classes of Weather-Types							
	I-c	I-i	I-a	II-c	II-i	III-c	III-i	III-a
January	-0.8	-3.2	-1.6	+1.0	+0.1	+1.9	+0.8	+0.5
February	+0.4	-2.8	-1.4	+0.6	-0.8	+1.6	+2.2	+0.9
March	-1.0	-2.6	-1.2	-0.3	-0.6	+1.8	+1.2	+1.6
April	-2.7	-1.3	-0.3	-2.4	+0.9	-0.1	+1.6	+2.6
May	-1.9	-1.8	+0.5	-1.1	+0.4	+0.3	+1.5	+2.3
June	-1.2	-1.8	+0.1	-1.8	-0.0	-0.3	+1.6	+2.5
July	-3.4	-1.7	+0.4	-1.4	+0.5	+0.7	+1.8	+2.0
August	-1.9	-1.5	+0.1	-1.0	+0.2	+0.5	+1.2	+2.3
September	-1.4	-1.2	-0.5	-1.4	+0.6	-0.0	+0.9	+1.7
October	-3.3	-1.2	-0.3	-1.9	-0.1	+2.1	+1.0	+1.3
November	-1.1	-1.5	-0.3	-0.7	+0.2	+1.1	+1.4	+0.8
December	+0.9	-1.9	-0.7	-0.2	+0.1	+1.5	+0.9	-0.5
Year	-1.8	-1.9	-0.7	-0.8	+0.2	+0.9	+1.3	-1.5

Mean future 10-day temperature index (I_T) is then computed according to:

$$I_T = \frac{1}{10} \sum_{i=1}^{10} (\Delta T_i + \tau') \qquad (4.25)$$

where, ΔT_i = estimated temperature departure (^{o}C) of day i corresponding to the weather-type, time of year and the corresponding class

τ' = normal pentad temperature (^{o}C) corresponding to day i

8) *Highest future 10-day temperature index* (hI_T)

The highest temperature index during the coming 10-day period was included as a variable in order to investigate its influence on maximum daily runoff. The value of hI_T is simply computed by selecting the day with the class having the highest value of ΔT and adding this value to the normal pentad value.

Table 4.8 Estimated mean temperature (τ') in Antholz (1953-1975) for periods of 5 days (pentads), computed from the running mean over 5 pentads (for the procedure of computation see chapter II.4.3).

Pentad	τ' (^oC)	Pentad	τ' (^oC)	Pentad	τ' (^oC)	Pentad	τ' (^oC)
1	-4.2	21	5.3	41	15.5	61	4.8
2	-4.3	22	5.8	42	15.6	62	4.1
3	-4.3	23	6.4	43	15.7	63	3.1
4	-4.2	24	7.2	44	15.8	64	2.0
5	-3.9	25	8.2	45	15.5	65	1.1
6	-3.5	26	9.0	46	15.1	66	0.1
7	-3.3	27	9.7	47	14.6	67	-0.9
8	-3.1	28	10.5	48	14.2	68	-1.5
9	-2.7	29	10.8	49	13.7	69	-1.9
10	-2.3	30	11.3	50	13.3	70	-2.5
11	-1.9	31	11.5	51	13.0	71	-3.1
12	-1.4	32	12.1	52	12.5	72	-3.4
13	-0.8	33	12.8	53	11.8	73	-3.9
14	-0.1	34	13.6	54	11.0		
15	-0.8	35	14.2	55	10.2		
16	1.8	36	14.9	56	9.3		
17	2.8	37	15.2	57	8.4		
18	3.8	38	15.3	58	7.4		
19	4.4	39	15.3	59	6.4		
20	4.8	40	15.5	60	5.6		

9) *Lowest future 10-day temperature index* (lI_T)

The lowest future 10-day temperature index has been computed using a procedure comparable to that used for hI_T.

10) *Mean future 10-day precipitation index* (I_P)

Because of the great variability of precipitation within the distinguished classes of weather-types it is far more difficult to define an index to re-

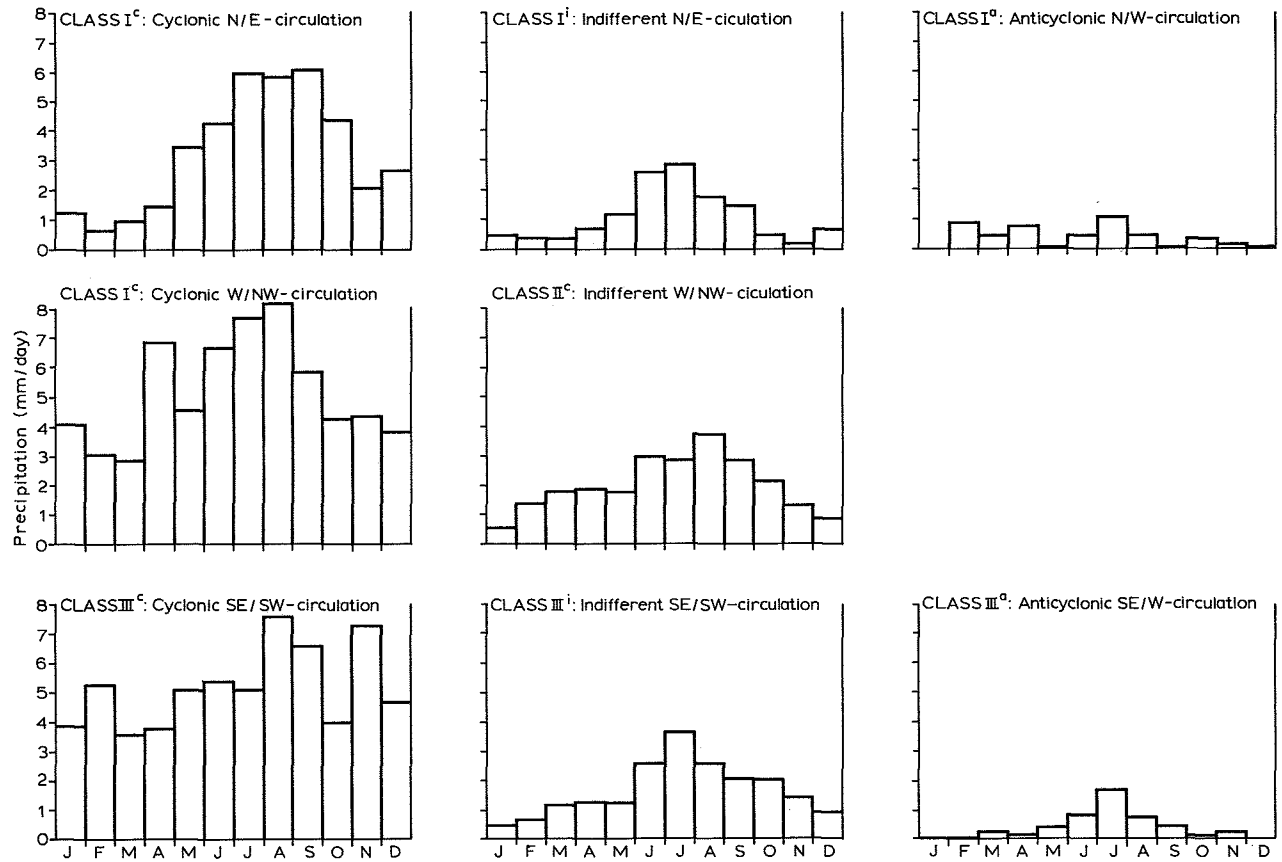


Fig. 4.8 Mean precipitation for the distinguished classes of weather-types for different months

present the impact of precipitation than for temperature. The impact of precipitation in our case is largely governed by laws of probability, even if the weather-type prediction is performed correctly. For example, during cyclonic W-circulation with the highest probability of a day with $P > 1$ mm (70% in summer), 30% of the days can still be regarded as rainless (see table 2.2c, chapter II. For model purposes one could thus think of an index based on median precipitation, mean precipitation or even one based on the probability density function of precipitation during the different classes. However, since none of these account for the probabilistic character, one is not regarded as being an advantage over another with respect to the aspect of probability. Therefore, the precipitation index proposed is based on the long-term monthly mean daily precipitation during the different classes of weather-types as presented in table 4.9 for each month (see also fig. 4.8). The value of I_P is computed according to

$$I_P = \frac{1}{10} \sum_{i=1}^{10} P_i \qquad (4.26)$$

where, P_i = expected precipitation on day i based on the forecast weather-type class and long-term average precipitation for that particular class during the corresponding month.

11) *Highest future 10-day precipitation index* (hI_P)

The value of hI_P is set equal to the highest long-term average precipitation for the weather-types occurring during the coming 10-day period.

12) *Lowest future 10-day precipitation index* (lI_P)

The value of lI_P is set equal to the lowest long-term average precipitation for the weather-types occurring during the coming 10-day period.

In addition to the above variables, a number of so-called derived future variables have been defined which result from a combination of initial variables and future variables.

13) $I_s \cdot I_T$

Since the snow-cover index I_s (variable 3) is defined as the amount of melt generated per degree above 0 ^{o}C, a measure for the melt to be generated

Table 4.9 Mean precipitation (mm/day) for the distinguished classes of weather-types for different months.

	Classes of Weather-Types							
	I-c	I-i	I-a	II-c	II-i	III-c	III-i	III-a
January	1.3	0.5	0.0	4.1	0.6	3.9	0.5	0.1
February	0.7	0.4	0.9	3.1	1.4	5.3	0.7	0.1
March	1.0	0.4	0.5	2.9	1.8	3.6	1.2	0.3
April	1.5	0.7	0.7	6.9	1.9	3.8	1.3	0.2
May	3.5	1.2	0.1	4.6	1.8	5.1	1.3	0.5
June	4.3	2.6	0.5	6.7	3.0	5.4	2.6	0.9
July	6.0	2.9	1.1	7.7	2.9	5.1	3.7	1.8
August	5.9	1.8	0.5	8.2	3.8	7.6	2.6	0.8
September	6.1	1.5	0.1	5.9	2.9	6.6	2.1	0.5
October	4.4	0.5	0.4	4.3	2.2	4.0	2.1	0.2
November	2.1	0.2	0.2	4.4	1.4	7.3	1.5	0.3
December	2.7	0.7	0.1	3.9	0.9	4.7	1.0	0.0
Year	3.5	1.1	0.4	5.2	2.2	5.3	1.7	0.5

during the coming 10-day period is given by $I_s . I_T$.

In a similar manner the following derived variables were incorporated:

14) $I_s . hI_T$

15) $I_s . lI_T$

B. Variables determined by direct method

All the above future variables can be extracted from daily forecast weather charts by translating the weather charts into weather-types (translation method) and by subsequent selection of corresponding index values considering the month of the year. The prediction of Q_{10}, lQ_{10} and hQ_{10}, therefore, is entirely based on empirically known statistical relations between weather-types and average meteorological impact in terms of temperature and precipitation.

On the other hand, parameters which are representative of meteorological impact on hydrology can also be derived directly from forecast weather charts (direct method). For example, there exists a highly significant linear relation between temperature and relative barometric topography (500/1000 mb-thickness) as shown by Kirchhofer (1971), who investigated this relation for a number of Alpine stations at different elevations. He also found the height of the 500 mb-level to explain an additional part of the variation of temperature for some stations and particular circulation types. Both parameters are presented in Schüepp's (1968) weather-type classification and have been incorporated to investigate their relation with medium-range temperature. Height of the 1000-mb level has also been incorporated in order to investigate its relation with medium-range precipitation.

These parameters can be extracted directly from forecast weather charts and in order to compare both methods they have been used subsequently for runoff prediction instead of the temperature- and precipitation indices derived by the translation method. The following additional future variables are thus proposed:

16) *Relative topography, i.e., 500/1000 mb-thickness* $(RT_{10})^*$

17) *Highest relative topography* $(hRT_{10})^*$

18) *Lowest relative topography* $(lRT_{10})^*$

19) *Altitude of 500 mb-level* $(AT_{500})^*$

20) *Altitude of 1000 mb-level* $(AT_{1000})^*$

21) *Highest altitude of 1000 mb-level* $(hAT_{1000})^*$

22) *Lowest altitude of 1000 mb-level* $(lAT_{1000})^*$

and the derived future variables:

23) $I_s \cdot RT_{10}$

24) $I_s \cdot hRT_{10}$

25) $I_s \cdot lRT_{10}$

* *In geop. dam - 500.*

3 SELECTION OF METEOROLOGICAL AND HYDROLOGICAL VARIABLES

3.1 Introduction

The combination of n observations and the above defined variables (say m) can be represented by a $n \cdot m$ matrix of observed results. The results of the individual observations, however, are not our primary concern. On the contrary, we are interested in the structure of the variables in terms of their mutual relationships and their importance for explaining the variance of the dependent variables. A picture of the structure of these a priori defined variables will be made using factor-analysis, with the aim of drawing conclusions about their general nature.

The selection of predictors from a set of a priori defined independent variables can be performed on the basis of factor-analysis, such that application of the final regression analysis can be restricted to a reduced number of variables. However, when applying step-wise regression, Seyhan (1976) has shown that there is no advantage in using factor-analysis to reducing the number of variables. The selection of predictors will therefore be performed by step-wise regression.

Factor-analysis and step-wise regression will be performed on the dependent and independent variables given in table 4.1. Furthermore the observed 10-day mean future precipitation (Pr_{10}) and 10-day mean maximum daily temperature (Tm_{10}) have been included in the factor-analysis, making a total of 30 variables. The analyses are performed for each month separately because of the seasonally dependent character of the hydrologic system. The months October till April are omitted because of the stable character of runoff during this period.

3.2 Application of Factor-Analyses

Factor-analysis can be used to gain an insight into the structure of a multivariate population. Theoretical background of factor-analysis and details of the present application are described in Appendix A. In summary, the technique represents a large number of correlated variables by a reduced number of uncorrelated factors. This allows interpretation of a multi-variate sample in terms of sets of mutually associated variables, each set represented by a single factor which explains part of the sample variance.

Several methods exist to represent a matrix of numbers by factors (usually related to the type of rotation of the axis of projection), most of which assume a priori theoretical considerations with respect to the structure of the relations. In cases where explicit knowledge about this structure is missing, as it is in our case, one can better use one of the so-called blind rotations, of which the varimax-method developed by Kaiser (1958) is generally regarded as the best standard procedure for automatic orthogonal rotation (Kouwer, 1971). This varimax-method leads to a simple factor structure with primarily high and low factor loadings, which simplifies interpretation especially in cases where no a priori arguments exist in favour of applying other methods (e.g. orthoblimax, oblimax).

An example matrix for a multi-variate sample of observations of the above defined variables is given in table 4.10 for the month of June. The number of observations during the 22 years of record with 20 days amounts to 440 cases*.

The objective of factor-analysis is to represent this matrix as well as possible with a minimum number of factors. The problem of how to decide upon the minimum, which is always reduced to subjectivity, is emphatically coped with by computing the factors one by one under the precondition that each new factor represents a part, as large as possible, of the remaining total variance of the matrix. The explained variance is denoted by the eigenvalue λ_j of the factor F_j where λ_j is the sum of squares of the loadings of the variables.

On the basis of the correlation matrix corresponding to the data matrix of table 4.10, and after rotation according to the varimax-criterion, the matrix of factor loadings was computed and is given in table 4.12 with deletion of the signs and loadings smaller than 0.5. From this matrix of factor loadings it follows that a total of 6 factors explain 79.8% of the total variance, with the following eigenvalues:

Factor	Eigenvalue	Explained Variance (%)	Cumulative expl. Var. (%)
1	11.92	39.7	39.7
2	5.88	19.7	59.4
3	2.15	7.1	66.5
4	1.54	5.1	71.6
5	1.33	4.5	76.1
6	1.12	3.7	79.8

* *Since the dependent variables according to the translation method are based on monthly-mean values, only the 1st till the 20th of each month have been selected as dates of forecast in the regression-analyses.*

Table 4.10 Data Matrix for June

Variable	Results of Observations ($x_{i,j}$)		
X_i	$x_{i,1}$	$x_{i,n}$	$x_{i,440}$
1	21.5		52.6
2	49.4		45.9
3	0.368		0.580
4	6.93		11.47
5	6.39		9.18
6	-0.92		-1.89
7	13.5		14.7
8	15.8		17.8
9	12.4		13.4
10	5.5		2.3
11	6.7		6.7
12	2.6		0.5
13	4.97		8.53
14	5.81		10.32
15	4.56		7.77
16	56.8		62.8
17	59.0		68.0
18	52.0		57.0
19	69.7		77.6
20	12.9		14.8
21	15.0		18.0
22	10.0		12.0
23	20.90		36.4
24	21.71		39.44
25	19.14		33.06
26	7.24		10.14
27	7.70		11.85
28	5.83		5.67
29	3.2		1.4
30	19.7		21.3

Table 4.11 MATRIX OF FACTOR LOADINGS FOR THE MONTH MAY

Variable X_i	Identification	$F_{j=1}$	F_2	F_3	F_4	F_5	F_6	F_7	Communality
i=1	API				0.60				0.50
2	ATI				0.78				0.76
3	I_s	0.99							0.99
4	Q_0	0.78							0.86
5	Q_{-10}	0.93							0.93
6	ΔQ							0.80	0.69
7	I_T						0.67		0.82
8	hI_T						0.85		0.79
9	lI_T								0.59
10	I_P					0.69			0.85
11	hI_P					0.81			0.70
12	lI_P			0.70					0.69
13	$I_s \cdot I_T$	0.97							0.99
14	$I_s \cdot hI_T$	0.96							0.98
15	$I_s \cdot lI_T$	0.96							0.96
16	RT_{10}		0.95						0.97
17	hRT_{10}		0.72						0.63
18	lRT_{10}		0.84						0.80
19	AT_{500}		0.84						0.97
20	AT_{1000}			0.85					0.88
21	hAT_{1000}			0.81					0.69
22	lAT_{1000}			0.51	0.53				0.63
23	$I_s \cdot RT_{10}$	0.97							0.99
24	$I_s \cdot hRT_{10}$	0.97							0.97
25	$I_s \cdot lRT_{10}$	0.96							0.98
26	Q_{10}	0.60	0.56						0.86
27	hQ_{10}	0.57							0.75
28	lQ_{10}	0.64							0.75
29	Pr_{10}					0.67			0.69
30	Tm_{10}		0.87						0.88
Eigenvalue	λ_j	11.67	4.58	2.62	1.85	1.54	1.26	1.03	24.56
$\sum_{k=1}^{j} \lambda_k$ (%)		38.9	54.2	62.9	69.1	74.2	78.4	81.9	

Table 4.12 MATRIX OF FACTOR LOADINGS FOR THE MONTH JUNE

Variable X_i	Identification	$F_{j=1}$	F_2	F_3	F_4	F_5	F_6	Communality
i=1	API						0.57	0.52
2	ATI				0.72			0.78
3	I_s	0.99						0.99
4	Q_0	0.85						0.87
5	Q_{-10}	0.91						0.94
6	ΔQ						0.75	0.60
7	I_T		0.51					0.85
8	hI_T							0.60
9	lI_T				0.63			0.70
10	I_P			0.76				0.80
11	hI_P			0.70				0.60
12	lI_P							0.41
13	$I_s.I_T$	0.95						0.98
14	$I_s.hI_T$	0.95						0.96
15	$I_s.lI_T$	0.96						0.98
16	RT_{10}		0.95					0.96
17	hRT_{10}		0.80					0.75
18	lRT_{10}		0.81					0.76
19	AT_{500}		0.85					0.96
20	AT_{1000}					0.60		0.84
21	hAT_{1000}					0.81		0.79
22	lAT_{1000}			0.67				0.58
23	$I_s.RT_{10}$	0.97						0.99
24	$I_s.hRT_{10}$	0.97						0.98
25	$I_s.lRT_{10}$	0.93						0.95
26	Q_{10}	0.69						0.86
27	hQ_{10}	0.70						0.78
28	lQ_{10}	0.56						0.67
29	Pr_{10}			0.77				0.66
30	Tm_{10}		0.82					0.86
Eigenvalue	λ_j	11.92	5.88	2.15	1.54	1.33	1.12	23.95
$\sum_{k=1}^{j} \lambda_k$ (%)		39.7	59.4	66.5	71.6	76.1	79.8	

Table 4.13 MATRIX OF FACTOR LOADINGS FOR THE MONTH JULY

Variable X_i	Identification	$F_{j=1}$	F_2	F_3	F_4	F_5	F_6	F_7	Communality
$i=1$	API							0.73	0.62
2	ATI							0.72	0.71
3	I_s	0.96							0.99
4	Q_0	0.76							0.83
5	Q_{-10}	0.92							0.91
6	ΔQ						0.90		0.82
7	I_T		0.76						0.75
8	hI_T							0.54	0.57
9	lI_T		0.63						0.70
10	I_P					0.68			0.79
11	hI_P					0.57			0.69
12	lI_P					0.72			0.62
13	$I_s \cdot I_T$	0.98							0.99
14	$I_s \cdot hI_T$	0.98							0.99
15	$I_s \cdot lI_T$	0.94							0.97
16	RT_{10}		0.93						0.93
17	hRT_{10}		0.80						0.71
18	lRT_{10}		0.85						0.80
19	AT_{500}		0.83	0.52					0.98
20	AT_{1000}			0.87					0.92
21	hAT_{1000}			0.71					0.77
22	lAT_{1000}			0.76					0.72
23	$I_s \cdot RT_{10}$	0.98							0.99
24	$I_s \cdot hRT_{10}$	0.98							0.98
25	$I_s \cdot lRT_{10}$	0.97							0.98
26	Q_{10}	0.80							0.91
27	hQ_{10}	0.69			0.55				0.82
28	lQ_{10}	0.59							0.64
29	Pr_{10}				0.78				0.79
30	Tm_{10}		0.88						0.87
Eigenvalue	λ_j	10.67	6.45	2.62	1.54	1.26	1.15	1.03	24.72
$\sum_{k=1}^{j} \lambda_k$ (%)		35.6	57.1	65.8	70.9	75.1	79.0	82.4	

Table 4.14 MATRIX OF FACTOR LOADINGS FOR THE MONTH AUGUST

Variable X_i	Identification	$F_{j=1}$	F_2	F_3	F_4	F_5	F_6	Communality
1	API	0.67						0.64
2	ATI							0.60
3	I_s	0.98						0.99
4	Q_0	0.73						0.82
5	Q_{-10}	0.92						0.92
6	ΔQ					0.78		0.62
7	I_T				0.86			0.90
8	hI_T				0.74			0.77
9	lI_T				0.80			0.70
10	I_P		0.88					0.86
11	hI_P		0.71					0.74
12	lI_P						0.60	0.67
13	$I_s.I_T$	0.99						0.99
14	$I_s.hI_T$	0.98						0.98
15	$I_s.lI_T$	0.98						0.98
16	RT_{10}			0.93				0.95
17	hRT_{10}			0.81				0.73
18	lRT_{10}			0.84				0.79
19	AT_{500}		0.58	0.75				0.95
20	AT_{1000}		0.89					0.89
21	hAT_{1000}		0.76					0.71
22	lAT_{1000}		0.69					0.54
23	$I_s.RT_{10}$	0.99						0.99
24	$I_s.hRT_{10}$	0.99						0.98
25	$I_s.lRT_{10}$	0.99						0.98
26	Q_{10}	0.58						0.87
27	hQ_{10}		0.59					0.76
28	lQ_{10}	0.70						0.82
29	Pr_{10}							0.80
30	Tm_{10}			0.79				0.90
Eigenvalue	λ_j	11.79	6.15	3.15	1.47	1.23	1.07	24.85
$\sum_{k=1}^{j} \lambda_k$ (%)		39.3	59.8	70.3	75.2	79.3	82.8	

Table 4.15 MATRIX OF FACTOR LOADINGS FOR THE MONTH SEPTEMBER

Variable X_i	Identification	$F_{j=1}$	F_2	F_3	F_4	F_5	F_6	F_7	Communality
i=1	API								0.56
2	ATI					0.52			0.71
3	I_s	0.97							0.99
4	Q_0	0.84							0.84
5	Q_{-10}	0.93							0.92
6	ΔQ							0.94	0.88
7	I_T				0.82				0.91
8	hI_T				0.68				0.77
9	lI_T				0.86				0.85
10	I_P			0.88					0.87
11	hI_P			0.75					0.61
12	lI_P								0.60
13	$I_s \cdot I_T$	0.97							0.98
14	$I_s \cdot hI_T$	0.97							0.97
15	$I_s \cdot lI_T$	0.94							0.97
16	RT_{10}		0.91						0.94
17	hRT_{10}		0.88						0.80
18	lRT_{10}		0.53						0.88
19	AT_{500}		0.91						0.96
20	AT_{1000}						0.64		0.86
21	hAT_{1000}								0.58
22	lAT_{1000}						0.77		0.68
23	$I_s \cdot RT_{10}$	0.97							0.98
24	$I_s \cdot hRT_{10}$	0.97							0.98
25	$I_s \cdot lRT_{10}$	0.91							0.96
26	Q_{10}	0.83							0.93
27	hQ_{10}	0.66							0.74
28	lQ_{10}	0.85							0.89
29	Pr_{10}			0.72					0.62
30	Tm_{10}		0.61						0.71
Eigenvalue	λ_j	10.9	5.47	2.98	1.89	1.34	1.26	1.03	25.10
$\sum_{k=1}^{j} \lambda_k$ (%)		36.4	54.7	64.6	70.9	75.4	79.6	83.1	

On the basis of the factor matrix the following important factors can be distinguished with regard to the different variables, each factor being composed of variables which are highly associated in a mutual sense.

Factor 1 explains the association between the following dimensions:

- Runoff (4, 5, 26, 27, 28)
- Snow-cover index I_s (3)
- $I_s \cdot$ Temperature index (13, 14, 15)
- $I_s \cdot$ Relative topography (23, 24, 25)

Factor 2 explains the association between the dimensions:

- Relative topography (16, 17, 18)
- Mean 10-day observed maximum temperature (30)
- Altitude of the 500 mb-level (19)
- Temperature index I_T (7)

Factor 3 explains the association between the dimensions:

- Precipitation index I_P (10, 11)
- Mean 10-day observed precipitation (29)
- Lowest altitude of 1000 mb-level (22)

INTERPRETATION

The dimension of runoff (factor 1) includes both future and antecedent runoff variables, with interrelationships as explained by autocorrelation phenomena described above. Occurrence of the snow-cover index I_s in this factor confirms the previous statement about the major influence of snow- and glacier conditions on medium-term runoff. The low coefficients of variation of RT_{10} (6.7%) and I_T (6.1%) as compared with that of I_s (26.4%), given below for the period May to September, explain the occurrence of the derived future factors $I_s \cdot I_T$ and $I_s \cdot RT_{10}$ in factor 1.

The coefficient of variation of I_s (%) for months May to September (period 1953-1974)

May	June	July	August	September
36.7	26.4	26.2	44.3	40.6

The composition of factor 1 is the same for all months (see tables 4.11 to 4.15), mainly as a result of the high coefficient of variation for I_s and its dominating influence on runoff. These high coefficients of variation stress the large year-to-year variation of snow- and glacier conditions even during late summer. The latter probably reflects variations in albedo between a fresh snow-cover on the glacier snout to pure glacier-ice.

Factor 2 is in agreement with the assumption of a linear association between relative topography and mean maximum temperature of the lower atmosphere (Tm_{10}). The temperature index I_T also occurs in this factor as a measure of mean 10-day maximum temperature. The combined occurrence of RT_{10} and Tm_{10} counts for all months. However, the weaker association between I_T and Tm_{10} causes I_T to occur as a single factor in May, August and September (compare the respective factor-matrices).

The joint occurrence of the precipitation index (I_P) and 10-day mean precipitation (Pr_{10}) in factor 3 confirms the significant association between the classes of weather-types and observed precipitation during a 10-day period. Another variable which is shown to be a significant indicator of mean 10-day precipitation is the 10-day mean 1000 mb-level, particularly in the month of August where it is included in this precipitation factor (August, factor 2).

Factors 4 to 6 in general represent single variables which are not significantly related to any of the other factors. In particular, the persistence factor ΔQ (variable 3) invariably occurs as an independent variable.

Although the representation of the total population by a reduced number of factors gives a good insight into the general nature of the total population, the relation between individual variables is somewhat obscured. The main relationships which are of further interest of course are those (a) between actual precipitation and parameters used for its representation and (b) between actual mean maximum temperature and corresponding representative parameters. The coefficients of correlation (r) are presented in table 4.16.

The relative topography (RT_{10}) occurs jointly with observed mean maximum temperature (Tm_{10}) in the same factor for each month and obviously proves to be a much better measure for temperature characteristics of the lower atmosphere than the weather-type temperature index (I_T).
The coefficient of correlation between observed precipitation (Pr_{10}) and the weather-type precipitation index (I_P) varies between 0.39 and 0.75. The second measure for 10-day mean precipitation AT_{1000} has notably lower correlations.

Table 4.16 The coefficients of correlation for Pr_{10} and Tm_{10} with parameters used for their representation. (period 1953-1974).

	May	June	July	August	September	
$r(Tm_{10}/RT_{10})$	0.88	0.88	0.90	0.87	0.53	Temperature
$r(Tm_{10}/I_T)$	0.40	0.68	0.66	0.62	0.56	
$r(Pr_{10}/I_P)$	0.39	0.57	0.55	0.75	0.68	Precipitation
$r(Pr_{10}/AT_{1000})$	-0.16	-0.40	-0.41	-0.70	-0.30	

3.3 Application of Step-Wise Regression

The selection of significant predictors from the set of a priori defined variables is performed by step-wise regression, where the preconditon is made that each newly introduced variable should lead to a significant increase in prediction precision of the dependent variable. For this, the criterion used was, that the standard error of estimate expressed as a percentage of the mean of the dependent variable, be reduced by at least 1%. The significance of the correlation coefficient and the regression coefficients are tested with Fischer's F-test (p=0.01) and the t-distribution (p=0.05) respectively as explained in Appendix A.

As an example of step-wise regression, table 4.17 shows the dependent variable Q_{10} as a linear function of an increasing number of independent variables for the month of June. The corresponding correlation matrix is shown in the upper part of the table. Application of the above significance criterion results in the following optimum prediction equation for Q_{10} in June:

$$Q_{10} = -13.39 + 0.127\,(I_s \cdot RT_{10}) + 0.351\,(RT_{10}) + 0.399\,I_P + 0.539\,Q_0 - 0.129\,ATI - 0.056\,API$$

This equation explains 79.7% of the variance of Q_{10} and estimates future 10-day runoff with a standard error of 1.45 mm/day, or 15.5% of the average Q_{10} in June.

Table 4.17 CORRELATION MATRIX FOR THE MONTH OF JUNE (PERIOD 1953-1974)

	API	ATI	I_s	Q_o	Q_{-10}	ΔQ	I_T	I_p	$I_s \cdot I_T$	RT_{10}	AT_{500}	AT_{1000}	$I_s \cdot RT_{10}$	Q_{10}
API	1	-0.33	-0.10	-0.20	-0.19	-0.03	0.13	-0.17	-0.06	0.18	0.18	0.14	-0.05	-0.15
ATI		1	0.41	0.65	0.64	-0.01	0.21	-0.04	0.45	0.04	0.07	0.10	0.41	0.23
I_s			1	0.82	0.91	-0.04	0.06	-0.21	0.97	0.05	0.14	0.26	0.97	0.63
Q_o				1	0.79	0.22	0.11	-0.14	0.82	0.17	0.23	0.27	0.84	0.70
Q_{-10}					1	-0.15	0.08	-0.14	0.89	-0.02	0.06	0.19	0.86	0.44
ΔQ						1	0.03	-0.03	-0.03	0.15	0.14	0.08	0.00	0.22
I_T							1	-0.66	0.29	0.03	0.63	0.55	0.17	0.15
I_p								1	-0.35	-0.50	-0.61	-0.63	-0.30	-0.16
$I_s \cdot I_T$									1	0.18	0.28	0.37	0.97	0.64
RT_{10}										1	0.94	0.58	0.28	0.49
AT_{500}											1	0.82	0.35	0.50
AT_{1000}												1	0.37	0.39
$I_s \cdot RT_{10}$													1	0.73
Q_{10}														1

RESULTS OF STEP-WISE REGRESSION (dependent variable = Q_{10}; number of cases = 440)

	Intercept	$I_s \cdot RT_{10}$	RT_{10}	I_p	Q_o	ATI	API	AT_{1000}	S.E.E.	t^{c*}	F^c	r	S.E.E.**	D(= r^2)
	0.30	0.316							2.17	21.0	442	0.728	23.2	0.530
	-13.30	0.284	0.236						1.95	8.0	291	0.794	20.8	0.630
	-21.44	0.301	0.326	0.548					1.81	6.7	232	0.826	19.3	0.682
	-21.21	0.195	0.338	0.482	0.243				1.73	5.1	192	0.842	18.5	0.709
	-13.96	0.127	0.332	0.435	0.551	-0.119			1.56	5.5	213	0.874	16.7	0.764
Selected →	-13.39	0.127	0.351	0.399	0.539	-0.129	0.056		1.45	5.8	206	0.893	15.5	0.797
	-14.08	0.125	0.325	0.498	0.524	-0.127	0.056	0.145	1.42	2.8	181	0.896	15.2	0.803

r = 0.893 S.E.E. = 1.45 mm/day — Lowest t^c = 5.8 — F^c = 206 — ** = % of $\overline{Q}_{10}$

D = 0.797 S.E.E.(% of mean Q_{10}) = 15.5% — $t^t_{(5\%)}$ = 1.6 — $F^t_{(1\%)}$ = 3.4 — * = lowest value

$\overline{Q}_{10}$ = 9.36 mm/day

REGRESSION COEFFICIENTS

MONTH	METHOD	INTERCEPT	INITIAL VARIABLES: API	ATI	Q_o	FUTURE VARIABLES, TRANSLATION METHOD: I_T	I'_p	$I_s \cdot I_T$	DIRECT METHOD: RT_{10}	AT_{1000}	$I_s \cdot RT_{10}$
MAY	A	-2.82	-	-	+0.303	+0.623	-0.233	+0.214	-	-	-
	B	-10.03		-0.032	+0.286	-	-	-	+0.274		+0.069
	C	-10.03		-0.032	+0.286			-	+0.274		+0.069
JUNE	A	+2.36		-	+0.428			+0.421	-		-
	B	-6.84	-	-0.114	+0.293		-	-	+0.260		+0.161
	C	-13.39	-0.056	-0.129	+0.593		+0.399	-	+0.351		+0.127
JULY	A	+0.47	-0.033	-	+0.282		+0.298	+0.718	-		-
	B	+1.06	-0.021		-		-	-			+0.277
	C	-0.03	-0.022		-		+0.300	-			+0.281
AUGUST	A	+0.69	-0.013		+0.416		+0.385	+0.267		-	-
	B	+6.89	-		+0.369		-	-		-0.323	+0.037
	C	+1.46	-0.012	-	+0.352		+0.377	-		-	+0.042
SEPTEMBER	A	-0.14	-	+0.016	+0.317		+0.182	+0.465		-	-
	B	+0.77		+0.018	+0.327		-	-		-0.037	+0.086
	C	+0.07	-	+0.013	+0.349	-	+0.157	-	-	-	+0.077

STATISTICS

MONTH	METHOD	r	D ($=r^2$)	S.E.E.	$\overline{Q}_{10}$ (mm/day)	S.E.E. (% of $\overline{Q}_{10}$)	Lowest* t	F^c	$F^t_{(1\%)}$
MAY	A	0.788	0.621	1.27	6.22	20.4	2.5	102	3.3
	B	0.871	0.759	1.02	6.22	16.4	2.8	199	3.3
	C	→ 0.871	0.759	1.02	6.22	16.4	2.8	199	3.3
JUNE	A	0.707	0.500	2.28	9.36	24.4	3.8	183	4.6
	B	0.824	0.679	1.82	9.36	19.4	5.8	223	3.3
	C	→ 0.893	0.797	1.45	9.36	15.5	5.8	206	2.8
JULY	A	0.823	0.677	1.19	7.37	16.1	5.7	194	3.3
	B	0.854	0.729	1.09	7.37	14.8	3.4	415	4.6
	C	→ 0.876	0.767	1.01	7.37	13.7	5.7	382	3.8
AUGUST	A	0.840	0.706	1.03	5.26	19.6	3.6	174	3.3
	B	0.843	0.711	1.02	5.26	19.4	3.7	241	3.8
	C	→ 0.863	0.745	0.96	5.26	18.3	3.4	215	3.3
SEPTEMBER	A	→ 0.878	0.771	0.48	3.08	15.6	4.8	292	3.3
	B	0.861	0.741	0.51	3.08	16.7	4.5	250	3.3
	C	0.874	0.764	0.49	3.08	15.9	3.8	281	3.3

* $t^t_{(5\%)} = 1.6$

Table 4.18 Results of regression analyses for the prediction of mean 10-day runoff (Q_{10}) according to the translation method (A), the direct method (B) and the combined method (C)

4 RESULTS OF RUNOFF-FORECASTING

4.1 Introduction

In this section the results of runoff-forecasting are presented and are derived according to the above example. The following forecasts are presented in succession

a) forecast of mean 10-day runoff (Q_{10})
b) forecast of highest 10-day daily runoff (hQ_{10})
c) forecast of lowest 10-day daily runoff (lQ_{10})

Each of the forecasts has been produced by both the translation-method (using parameters translated from forecast weather-charts on the basis of classes of weather-types) and by the direct-method (on the basis of parameters directly derived from forecast weather-charts) as presented in table 4.1. In addition, a step-wise regression procedure has been performed on the combined set of translation- and direct-method parameters in order to find the optimum regression equation.

The analyses have been performed separately for each month of May to September. The remaining months (October to April) have not been subjected to regression analyses because of the rather stable character of runoff during these months.

The regression equations are based partly on future independent variables computed for each 10-day period following the date of forecast. Since the independent variables according to the translation-method are based on monthly-mean values, only the 1^{st} until the 20^{th} of each month have been selected as dates of forecast in the regression analyses.

4.2 Forecasting Mean 10-day Daily Runoff

Regression analysis results in an equation with the following two important aspects:

a) The regression equation as the basis for prediction of the dependent variable.
b) The sequential order in which the independent variables appear in the regression equation by step-wise regression. This sequence is immaterial for the final results of forecasting but provides a valuable tool for interpretation and recognition

of the relevance of different independent variables, especially in this case with respect to the time of year.

Therefore, besides presenting a table with intercept and regression coefficients in combination with statistical parameters, the regression equations are also shown for each month with the regression coefficients in sequential order of importance.

Results of Regression Analyses

Results of the regression-analyses are presented in table 4.18 for each month (May till September) in accordance with the three methods, i.e., the *translation-method*, the *direct-method* and the *combined-method*.

In all months except September the direct-method leads to better results (compare the values of r, D ($D=r^2$) and S.E.E.). This is in agreement with the results reported in table 4.16, which concerns a comparison between the temperature-index I_T and the relative topography RT_{10} as a measure to represent heat-input by comparing their correlations with measured maximum temperatures (Tm_{10}). From this table it can be seen that except for September the coefficients of correlation between mean 10-day maximum temperature (Tm_{10}) and RT_{10} exceed those between Tm_{10} and I_T.

From the analyses in table 4.16 it also appears that the precipitation index I_P is the best measure for representing mean 10-day precipitation. This explains why the combined approach leads to the best regression-equations with both RT_{10} (according to the *direct-method*) and I_P (according to the *translation-method*), except for September where the differences are minor.

The coefficients of multiple-correlation (r, table 4.18) from the combined-method vary between 0.87 and 0.89 with the explained variance ($D=r^2$) between 76% and 80%. The S.E.E.-values expressed as a fraction of the mean Q_{10} vary between 18.3% and 13.7% and are regarded as satisfactory.

The Structure of the Regression-Equations

In table 4.19 the regression equations have been presented with the independent variables in sequential order in accordance with their contribution in explaining the variance of the dependent variables. The occurrence of the variables will be discussed separately with respect to the time of year.

Table 4.19 Regression equations for forecasting mean 10-day runoff according to the *translation-method* (A), the *direct-method* (B) and the *combined-method* (C), for the months May to September (River Ahr, gauging station Steinhaus)

MONTH	*METHOD*	*REGRESSION EQUATION*
MAY	A	$Q_{10} = -2.82 + 0.214\,(I_s \cdot I_T) + 0.303\,Q_o + 0.623\,I_T - 0.233\,I_p$
	B	$Q_{10} = -10.03 + 0.069\,(I_s \cdot RT_{10}) + 0.274\,RT_{10} + 0.286\,Q_o - 0.032\,ATI$
	C	Result not improved as compared with B
JUNE	A	$Q_{10} = +2.36 + 0.421\,(I_s \cdot I_T) + 0.428\,Q_o$
	B	$Q_{10} = -6.84 + 0.161\,(I_s \cdot RT_{10}) + 0.260\,RT_{10} + 0.293\,Q_o - 0.114\,ATI$
	C	$Q_{10} = -13.39 + 0.127\,(I_s \cdot RT_{10}) + 0.351\,RT_{10} + 0.399\,I_p + 0.539\,Q_o - 0.129\,ATI - 0.056\,API$
JULY	A	$Q_{10} = +0.47 + 0.718\,(I_s \cdot I_T) + 0.282\,Q_o - 0.033\,API + 0.298\,I_p$
	B	$Q_{10} = +1.06 + 0.277\,(I_s \cdot RT_{10}) - 0.021\,API$
	C	$Q_{10} = -0.03 + 0.281\,(I_s \cdot RT_{10}) + 0.300\,I_p - 0.022\,API$
AUGUST	A	$Q_{10} = +0.69 + 0.416\,Q_o + 0.385\,I_p + 0.267\,(I_s \cdot I_T) - 0.013\,API$
	B	$Q_{10} = +6.89 + 0.369\,Q_o - 0.323\,AT_{1000} + 0.037\,(I_s \cdot RT_{10})$
	C	$Q_{10} = +1.46 + 0.352\,Q_o + 0.377\,I_p + 0.042\,(I_s \cdot RT_{10}) - 0.012\,API$
SEPTEMBER	A	$Q_{10} = -0.14 + 0.317\,Q_o + 0.182\,I_p + 0.465\,(I_s \cdot I_T) + 0.016\,ATI$
	B	$Q_{10} = +0.77 + 0.327\,Q_o + 0.086\,(I_s \cdot RT_{10}) + 0.018\,ATI - 0.037\,AT_{1000}$
	C	$Q_{10} = +0.07 + 0.349\,Q_o + 0.077\,(I_s \cdot RT_{10}) + 0.157\,I_p + 0.013\,ATI$

4.52

The derived variables $I_s.I_T$ *and* $I_s.RT_{10}$ (FUTURE FACTORS)

During the months May to July, the derived variables $I_s.I_T$ (*translation-method*) and $I_s.RT_{10}$ (*direct-method*) appear as the first independent variables in the respective regression equations and thus explain the largest part of the variance of the dependent variable. The importance of these variables, representing the heat-input effect on the nivo-glacial system, is in agreement with the major contribution of the nivo-glacial system to runoff during these months. The decreasing importance of the nivo-glacial system in late-summer and autumn is reflected in the occurrence of $I_s.I_T$ and $I_s.RT_{10}$ as the second or even the third variable in the regression equations found for August and September. In all months $I_s.RT_{10}$ replaces $I_s.I_T$ in the combined-method equation as a better measure for heat-input generating runoff.

The autoregressive term Q_0 (INITIAL FACTOR)

The second important variable in the regression equation is the autoregressive term Q_0. It even appears as the first independent variable in August and September. The importance of autocorrelation during these months is probably explained from the fact that the glacier-tongues with their snowfree surfaces and low albedos lie almost continuously below the 0 ^{o}C isotherm and thus sustain a rather stable glacier-melt runoff irrespective of weather-type.

The precipitation-index I_P *and 1000 mb-level* AT_{1000} (FUTURE FACTORS)

The importance of both variables for the representation of precipitation, I_P and AT_{1000}, is minor during the snow-melt months and becomes progressively important towards late-summer and autumn.

In May, the precipitation-index even appears with a negative regression coefficient and gives a decrease in runoff with increasing precipitation. This is a typical phenomenon of the nival-system: a higher precipitation-index is connected with lower radiation intensities and heat advection, thus decreasing snow-melt, all other factors being equal.

The minor importance of precipitation also explains why the combined-method with a translation- and a direct-method component does not lead to a higher coefficient of correlation than does the direct-method equation.

The progressive importance of I_p for the representation of precipitation follows from the shift to the left in the regression equations towards September and reflects the change from the mainly nivo-glacial regime in spring towards the mainly pluvio-glacial regime in late-summer and autumn.

The Antecedent Temperature Index ATI (INITIAL FACTOR)

The ATI explains a sufficient part of the variance of Q_{10} to appear in the regression equations with negative coefficients in May and June. These negative coefficients reflect the importance of the nival-system for runoff since higher values of ATI - with all other variables held constant (including Q_0) - implies a lower snow-cover index I_s and thus lower values of future runoff. The former assumptions on the introduction of ATI (Ch. IV, sect. 2.3) as a measure for snowpack-ripening and heat absorption capacity before reaching a threshold-value for snow-melt drainage may occur, thus are not confirmed by the regression analyses. According to these former assumptions, ATI is expected to have positive coefficients but the meaning of ATI as a measure for approaching the mentioned threshold-value is probably obscured as a result of the highly significant positive correlation between the snow-cover index I_s and ATI (see correlation matrix of table 4.17).

The Antecedent Precipitation Index API (INITIAL FACTOR)

The API explains a sufficient part of the variance of Q_{10} to appear in the regression equations for June to August, be it last or almost last. It thus explains the smallest part of the variance of Q_{10}. However, API with negative coefficients does not explain initial soil moisture conditions but most probably points at the importance of antecedent conditions related to the nivo-glacial system*. High values of API imply a decrease of the runoff from the nivo-glacial system while the increased contribution of the pluvial system decreases faster under pure recession flow.

* *The relatively weak importance of initial moisture conditions for medium-range runoff forecasting is in agreement with the relatively small storage capacity of thin soils (typical for high mountain catchments) and solid rocks in the Ahr valley. In general, the influence of initial moisture conditions is much higher for estimation of direct-runoff and peak-runoff.*

REGRESSION COEFFICIENTS

MONTH	METHOD	INTERCEPT	INITIAL VARIABLES: API	ATI	I_s	Q_o	FUTURE VARIABLES: TRANSLATION METHOD: I_T	I_p	$I_s \cdot I_T$	$I_s \cdot hI_T$	DIRECT METHOD: hRT_{10}	AT_{1000}	$I_s \cdot hRT_{10}$
MAY	A	-7.11	-	-	-	+0.418	+1.121	-	+3.090	-	-	-	-
	B	-10.87		-0.101		+0.542	-		-		+0.307		+0.109
	C	-16.28		-0.103		+0.583	+0.788			-	+0.264		+0.056
JUNE	A	+2.56		-		+0.345	-			+0.805	-		-
	B	+9.16		-0.219		+0.611				-			+0.172
	C	-		-		-		-		-			-
JULY	A	-4.36		+0.054		+0.135		+0.436		+1.190			
	B	-4.97		+0.076		-		-		-			+0.360
	C	-		-	-	-		-					-
AUGUST	A	-0.50			+3.532	+0.607		+0.863			-	-	
	B	+20.78			-	+0.689		-			-0.137	-0.612	
	C	-	-			-	-	-			-	-	
SEPTEMBER	A	-1.49	+0.013	-		+0.685	+0.173	+0.360					
	B	+0.09	+0.017	+0.026		+0.705	-	-					
	C	-	-	-	-	-	-	-	-	-	-	-	-

STATISTICS

MONTH	METHOD	r	D ($=r^2$)	S.E.E.	$\overline{hQ}_{10}$ (mm/day)	S.E.E. (% of $\overline{hQ}_{10}$)	Lowest* t	F^c	$F^t_{(1\%)}$
MAY	A	0.687	0.472	2.38	9.03	26.4	2.2	110	3.8
	B	0.749	0.561	2.16	9.03	23.9	4.4	118	3.3
	C	0.776	0.602	2.06	9.03	22.8	3.4	111	3.0
JUNE	A	0.696	0.484	2.93	12.04	24.3	4.5	171	3.8
	B	0.743	0.552	2.74	12.04	22.8	5.2	150	3.8
	C	-	-	-	-	-	-	-	-
JULY	A	0.734	0.539	2.37	9.75	24.3	4.6	141	3.3
	B	0.700	0.490	2.49	9.75	25.5	5.6	176	4.6
	C	-	-	-	-	-	-	-	-
AUGUST	A	0.733	0.537	2.52	7.11	35.4	2.6	143	3.8
	B	0.724	0.524	2.56	7.11	36.0	3.7	136	3.8
	C	-	-	-	-	-	-	-	-
SEPTEMBER	A	0.729	0.531	1.13	3.77	30.0	2.9	99	3.3
	B	0.690	0.476	1.19	3.77	31.5	3.2	105	3.8
	C	-	-	-	-	-	-	-	-

* $t^t_{(5\%)} = 1.6$

Table 4.20 Results of regression analyses for the prediction of highest 10-day daily runoff (hQ_{10}) according to the *translation method* (A), the *direct method* (B), and the *combined method* (C)

4.3 Forecasting Highest 10-day Daily Runoff

Results of the regression analyses for prediction of highest daily runoff during the coming 10-day periods are presented in table 4.20.

The coefficients of correlation (r) for the regression equations with variables selected freely according to the *combined method* vary between 0.73 (September) and 0.78 (May), with explained variances ($D = r^2$) of the forecast variable hQ_{10} lying between 53% and 60%. The values of S.E.E. expressed as a fraction of the mean hQ_{10} vary between 30% and 23% respectively.

Highest runoff occurrences may result from both the nivo-glacial and the pluvial regime. As far as the nivo-glacial regime is concerned, the highest daily runoff values occur as a result of high heat-inputs into the catchment. However, the fact that values of the temperature-index I_T, as the mean expectation of 10-day mean temperature, are positively correlated with the highest daily heat-input explains the appearance of I_T and the derived variable $I_s \cdot I_T$ in the regression equations. The highest relative topography hRT_{10} *(direct-method)* as a measure of the actual highest daily heat-input and the *derived direct-method variable* $I_s \cdot hRT_{10}$ lead to the highest values of r in May and June, thus reflecting the importance of the nivo-glacial system for extreme runoff occurrences in spring and early-summer.

As far as the pluvial regime is concerned, the highest daily runoff values are primarily the result of short-period rainfalls rather than 10-day mean precipitation. Also in this case, the positive correlation between the precipitation-index I_p, as the mean expectation of 10-day mean rainfall and the highest daily rainfall in that particular period, explains the appearance of I_p as an independent variable in the regression equation for the prediction of hQ_{10}. The variable I_p only appears in the equations for July to September, again reflecting the importance of the pluvial system for peak runoff when the contribution of the nival system has been reduced.

Although the results of the regression analyses must be regarded as unsatisfactory for purposes of highest 10-day daily runoff prediction (with S.E.E.-values varying between 30% and 23%), the occurrence of the different variables in the equations for each month show the shift from the nivo-glacial system towards the pluvial system through the year with respect to their importance for extreme runoff occurrences.

REGRESSION COEFFICIENTS

MONTH	METHOD	INTERCEPT	INITIAL VARIABLES			FUTURE VARIABLES: TRANSLATION METHOD				FUTURE VARIABLES: DIRECT METHOD					
			API	ATI	Q_o	I_T	I_p	$I_s \cdot I_T$	$I_s \cdot lI_T$	lRT_{10}	AT_{500}	AT_{1000}	lAT_{1000}	$I_s \cdot RT_{10}$	$I_s \cdot lRT_{10}$
MAY	A	-0.23	-	-	+0.180	+0.232	-	-	+0.219	-	-	-	-	-	-
	B	-1.39			+0.151	-			-	+0.092			-0.048		+0.047
	C	-			-				·	-			-		-
JUNE	A								·						
	B								·					-	
	C	-	-	-	-				-						
JULY	A	+2.43	-0.007	+0.016	+0.056				+0.249						-
	B	+2.41	-0.005	+0.016	+0.053				-						+0.064
	C	-	-	-	-		-	-	·						-
AUGUST	A	+1.54	-0.013		+0.217		+0.119	+0.295	·		-	-		-	
	B	-0.78	-		+0.177		-	-	·		+0.084	-0.245		+0.053	
	C	-	-		-		-	-	-		-	-		-	
SEPTEMBER	A	+0.50	-0.011		+0.241		+0.148	+0.517	·			-		-	
	B	+1.27	-0.011		+0.238		-	-	-			-0.028		+0.101	
	C	+0.57	-0.012	-	+0.241	-	+0.117	-	-	-	-	-	-	+0.100	-

STATISTICS

MONTH	METHOD	r	D $(=r^2)$	S.E.E.	$\overline{lQ}_{10}$ (mm/day)	S.E.E. (% of $\overline{lQ}_{10}$)	Lowest* t	F^c	$F^t_{(1\%)}$
MAY	A	0.720	0.518	0.86	4.13	20.8	3.9	133	3.8
	B	→ 0.802	0.643	0.74	4.13	17.9	4.1	166	3.3
	C	-	-	-	-	-	-	-	-
JUNE	A	< 0.6							
	B	< 0.6							
	C	< 0.6	-	-	-	-	-	-	-
JULY	A	0.621	0.386	0.58	5.23	11.1	2.7	58	3.0
	B	→ 0.630	0.397	0.58	5.23	11.1	2.2	61	3.3
	C	-	-	-	-	-	-	-	-
AUGUST	A	0.786	0.618	0.70	4.16	16.8	5.7	149	3.3
	B	→ 0.824	0.679	0.64	4.16	15.4	7.9	195	3.8
	C	-	-	-	-	-	-	-	-
SEPTEMBER	A	0.881	0.776	0.40	2.67	14.8	6.6	300	3.3
	B	0.877	0.769	0.40	2.67	15.1	4.5	289	3.3
	C	→ 0.887	0.787	0.39	2.67	14.5	7.0	319	3.3

* $t^t_{(5\%)} = 1.6$

Table 4.21 Results of regression analyses for the prediction of lowest 10-day daily runoff (lQ_{10}) according to the *translation method* (A), the *direct method* (B), and the *combined method* (C)

4.4 Forecasting Lowest 10-day Daily Runoff

Results of the regression analyses for prediction of the lowest daily runoff during the coming 10-day periods are presented in table 4.21.

The correlation coefficients (r) for the regression equations with variables selected freely according to the *combined-method* vary between values < 0.6 for June and 0.89 for September, with explained variances ($D = r^2$) of the forecast variable lQ_{10} between < 36% and 79%.

The occurrence of lowest runoff is related to the activity of both the nivo-glacial and the pluvial systems, especially with respect to recession flow. The incorporation of lAT_{1000} in May with a negative coefficient, showing the negative correlation between atmospheric pressure and lowest runoff, is characteristic for the beginning of the active melting period, since precipitation is still falling as snow in the larger part of the catchment and thus both the nivo-glacial and pluvial systems are in recession flow.

For June, values of r are smaller than 0.6 and the regression coefficients have been deleted therefore. For August, the value of r again exceeds 0.8. During late-summer lowest runoff values occur during longer dry and cool periods during which both systems are mainly in recession flow. This explains the incorporation of $I_s \cdot RT_{10}$ as lower values of RT_{10} imply lower snow- and glacier melt contribution. In the same way the negative regression coefficient of AT_{1000} corresponds to a lower input of precipitation.

Also for low runoff occurrences the importance of antecedent conditions related to the nivo-glacial system follows indirectly from the occurrence of negative regression coefficients of API from July till September. High values of API imply a decrease of the rather stable runoff from the nivo-glacial systems while the increased contribution of the pluvial system decreases faster under pure recession flow.

The regression equations for lowest daily runoff are not regarded to be of practical importance. However, also here the relative importance of both the nivo-glacial and the pluvial systems for lowest runoff values as a relevant characteristic of the overall runoff regime, follows from the regression analyses with weather-type related parameters.

5 CONCLUSIONS

The following conclusions have been drawn with respect to runoff-forecasting on the basis of forecast weather-charts:

A. With Respect to the Prediction of 10-day Mean Runoff (Q_{10})

1) Weather-maps of the 1000 and 500-mb levels contain sufficient information to predict 10-day mean runoff from nivo-pluvio-glacial catchments by translation of the weather-charts into weather types and subsequent computation of a precipitation-index I_P and temperature-index I_T.

2) *Starting from forecast weather-charts, which are assumed to be correct,* the use of relative topography RT_{10} (difference between 1000 mb- and 500 mb-level as an average for the central Alpine area) appears to be a better measure for heat-input into the catchment than the temperature-index I_T, extracted from the weather-charts on the basis of a translation into weather-types.

3) The precipitation-index I_P, computed on the basis of weather-types and extracted from the classes of weather-charts (*translation-method*), appears to be the best index for the representation of precipitation in the catchment.

4) Combination of the precipitation-index I_P (translation-method) and relative topography RT_{10} (direct-method) generally leads to the best results, especially during the months June to August where both the nivo-glacial and the pluvial sub-systems may provide a considerable contribution to runoff.

5) The persistence factor ΔQ does not explain a significant part of the dependent variable, and this situation can be explained from the *rather low characteristic times (about 2-3 days) of the fast reacting* nival and pluvial sub-systems (see table 4.2).

6) There exists a clear shift of contributing variables in the monthly regression equations from spring towards late-summer and autumn. During spring the predominant influence of the nivo-glacial sub-system on runoff is reflected by indices which represent the heat-input into the catchment. The influence of these indices gradually diminishes with increasing importance of the precipitation-index, and reflects the growing influence of the pluvial sub-system in late-summer and autumn.

7) Multiple correlation coefficients between 10-day mean future runoff Q_{10} and selected independent variables vary between 0.86 and 0.89. The explained variances of the dependent variable Q_{10} vary between 71% and 80%. The values of S.E.E., expressed as a fraction of the mean of Q_{10} vary between 18.3% and 13.7% and are regarded as satisfactory.

B. With Respect to the Prediction of Highest 10-day Daily Runoff

8) Multiple correlation coefficients between highest 10-day daily runoff hQ_{10} and selected independent variables vary between 0.73 and 0.78, with explained variances of the dependent variable hQ_{10} varying between 53% and 60%. These are regarded as unsatisfactory for purposes of forecasting.

9) The occurrence of the different variables in the regression equations for each month clearly shows the shift from the nivo-glacial sub-system towards the pluvial sub-system through the year with respect to their importance for extreme-runoff occurrences.

C. With Respect to the Prediction of Lowest 10-day Daily Runoff

10) Multiple correlation coefficients between lowest 10-day daily runoff lQ_{10} and selected independent variables vary between values <0.6 in June and 0.89 in September. Except for that for September, these regression equations are regarded to have no practical meaning.

11) Be it to a lesser extent than the regression equations for Q_{10} and hQ_{10}, the equations for lQ_{10} still show the relative importance of both the nivo-glacial and the pluvial sub-systems for the occurrence of lowest runoff values on the basis of weather-type related parameters.

S U M M A R Y

In this thesis relations have been described between runoff phenomena of an Alpine catchment and weather situations. Weather situations are determined from weather-charts by translation into weather types. On this basis a weather type based model has been developed for medium-range runoff forecasting. By doing this, a new method has been introduced for medium-range runoff forecasting, to fill the gap between methods for short-range (up to a few days) and long-range forecasting (a few weeks to months). Likewise, an impulse is given to a new form of integration between the disciplines of *hydrology* and *meteorology*, leading to a weather-type based approach to runoff forecasting. The forecast of 1000 mb and 500 mb weather-charts ten days in advance, for western Europe, as produced by the "European Centre for Medium Range Weather Forecast (ECMWF)" in Reading, England, is used as a guide-line for the medium-range forecast period.

The method has been applied to the upstream part of the Alpine catchment of the river Ahr (fig. 1.1, p. 1.1). The catchment is situated immediately on the southern side of the Central Alpine ridge of the Zillertal Alps. It covers 148 km^2 and elevation ranges from 1035 m to 3499 m a.s.l. (fig. 1.2, p. 1.3). Hydrological and meteorological data from the 23-year period 1953-1975 were used for the investigation.

As a result of periodical storage of snow and ice and the related nivo-glacial regime-components in the river discharge, Alpine catchments are of considerable importance for hydro-power generation and form potential water yielding areas for water-supply purposes. Medium-range forecasts of river runoff are important for optimal hydrologic management of these catchments (flood control, reservoir regulation, etc.).

As a result of storage and travel-time effects hydrological systems have the property to delay the input of rainfall and snowmelt during runoff generation. This offers the possibility of estimating future runoff without using precipitation and temperature forecasts. The use of this delay plays an important role in current runoff forecasting methods. According to these methods the forecast period is determined by the natural lag for the smaller catchments, while for the larger catchments the behaviour of flood waves in the channel-systems may be of additional importance for the forecast period.

The natural lag of small Alpine catchments restricts the forecast period to

one or two days. Therefore, for forecast periods exceeding the natural lag of the catchment, one is committed to the use of precipitation and temperature forecasts which are unsatisfactory for this application.

This thesis consists of four chapters. In chapter I the hydrologic behaviour of the river Ahr is analysed and described in terms of pluvial, nival and glacial regime-components and their importance to the total runoff regime, dependent on the time of year (fig. 1.8, p. 1.10 and fig. 1.14, p. 1.16). The nival and glacial subsystems are both responsible for an extremely high baseflow outside the winter periods and so prevent the river from reaching low flow levels during long periods without precipitation (fig. 1.15, p.1.17).

In order to investigate the relation between runoff behaviour and weather-types one is committed to the use of an objective classification of those types. The concept of weather-type classification is discussed and an overview of existing classification systems is presented in chapter II. As both precipitation and temperature are the most important factors which determine the input into the runoff generating system, the association between these meteorological parameters and distinguished weather types was used as a criterion for the classification system to be used in this investigation. On this basis the classification system of Schüepp (1968) gives the best results.

Schüepp's classification system was used as a basis for the current investigation. Using this system (scheme 2.2, p. 2.14) in combination with observed precipitation and temperature data from the Ahr valley and its direct surroundings, eight hydrologically relevant classes have been defined, based on:

a) a distinction of air-masses in combination with temperature-departures from normal,
b) a distinction on cyclonicity (scheme 2.5, p. 2.36 & p. 2.37).

The relations between the above classes of weather-types and runoff are described in chapter III on the basis of selected statistical parameters. The difference in character of runoff during the different classes is clearly evident from a comparison of runoff variability (fig. 3.4, p. 3.7) and from a comparison of mean daily discharge changes (fig. 3.5, p. 3.8). Anticyclonic N/E-circulation produces a decrease in discharge, on average, during almost all months, while cyclonic SE/NW-circulation gives an increase in discharge throughout the year on average. However, the differences in mean runoff during both these classes are comparatively small (fig. 3.3, p. 3.5).

This demonstrates that runoff is highly associated with the character of the weather during preceding classes. This is also clearly shown by an analysis of variance of runoff values within the different classes.

Therefore, the *character* of the weather-type determines the *character* of runoff in terms of its variability, its increase or decrease. The *level* of runoff, however, is to a great extent related to the *level* of the antecedent conditions and autocorrelation. Antecedent conditions are determined mainly by extent and physical properties of the nivo-glacial subsystems. The autocorrelation is related to characteristic times of the pluvial, nival and glacial subsystems active during the preceding weather-types.

Statistical relations were established between classes of weather-types and:

1) expectations of temperature departures from normal,
2) expectations of precipitation.

On this basis a weather-type based model has been developed for forecasting mean runoff for medium-range periods (10 days). The model has been described in chapter IV and is based on a multiple regression analysis between the dependent variable (runoff) and a group of independent variables. The latter are split into INITIAL VARIABLES, related to catchment conditions known at the date of forecast and FUTURE VARIABLES which can be extracted from forecast weather-charts. The future variables are subsequently divided into:

a) variables determined from forecast weather-charts by translation into weather-types (TRANSLATION METHOD),
b) variables determined directly from forecast weather-charts (DIRECT METHOD).

The regression analyses were performed separately for each month from May to September. The other months have not been analysed because of the stable character of runoff during this period.

As the primary aim was to evaluate the applicability of forecast weather-charts for purposes of runoff forecasting, a clear distinction has been made between:

a) forecasting weather-charts (the field of meteorology)
b) the use of forecast weather-charts for medium-range runoff forecasting.

In accordance with forecast weather-charts produced by the ECMWF, ten days in advance, the model has been applied for the prediction of:

1) mean runoff during the coming 10-day period,

2) highest daily runoff during the coming 10-day period,

3) lowest daily runoff during the coming 10-day period.

The model was tested using the 22-year period (1953-1974). A combination of future variables, determined by both the translation and the direct method, led to the best results. This combination is called the COMBINED METHOD. Forecast of 10-day mean runoff produced the most satisfactory results, with correlation coefficients between observed and forecast runoff varying between 0.86 (August) and 0.89 (June) and with explained variances of respectively 75% and 80%.

Correlation coefficients derived for forecasting highest and lowest daily runoff during the coming 10-day periods varied between 0.73 (June) and 0.78 (May) for the highest and between 0.54 (June) and 0.89 (September) for the lowest daily runoff.

The variables in the regression equations give a clear picture of the relative importance of pluvial, nival and glacial subsystems to the total runoff regime as a function of the time of year.

Z U S A M M E N F A S S U N G

In dieser Dissertation werden die Zusammenhänge beschrieben zwischen dem Abflussverhalten eines alpinen Flussgebietes und der gesamten Wettersituation, wie diese durch eine Übersetzung nach Wettertypen den Wetterkarten entnommen werden kann. Auf diesem Grund wurde ein auf Wettertypen basiertes Modell entwickelt für Abflussvorhersagen auf mittelfristigen Termin. In dieser Weise wird eine neue Methode eingeführt für mittelfristige Abflussvorhersagen, zur Ausfüllung der Lücke zwischen Methoden für kurzfristige Abflussvorhersagen (auf einige Tage) und Methoden für langfristige Abflussvorhersagen (auf einige Wochen bis Monate). Damit wird gleichzeitig ein erster Versuch gemacht für eine neue Integration der Fachkreisen der *Hydrologie* und *Meteorologie*, führend zu einer auf Wettertypen basierte Methodik für Abflussvorhersagen. Als Richtlinie für den mittelfristigen Termin wurden die 10-tägigen Perioden genommen, worüber von dem "European Centre for Medium Range Weather Forecast (ECMWF)", in Reading, England, für West-Europa 1000 mb- und 500 mb-Karten im voraus hergestellt werden.

Die Methode wurde in Anwendung gebracht für das alpine Flussgebiet der Ahr oberhalb Steinhaus (Fig. 1.1, S. 1.1). Das Flussgebiet misst 148 km^2 und die Höhe wechselt zwischen 1035 m und 3499 m ü.M. (Fig. 1.2, S. 1.3). Es ist an der südlichen Seite des Zentralalpenhauptkammes der Zillertaler Alpen gelegen. Für die Untersuchung wurden hydrologische und meteorologische Daten verwendet über die 23-jährige Periode 1953-1975.

Alpine Flussgebiete sind durch die zeitliche Speicherung von Schnee und Eis und die inhärente nivo-glaziale Komponente im Abflussregime von grosser Bedeutung für Energieerzeugung und sind wegen ihrer grossen Vorratsbildung potentielle Wassergewinnungsgebiete. Die mittelfristige Vorhersage von Abflüssen ist notwendig für optimale wasserwirtschaftliche Verwaltung von diesen Flussgebieten.

Weil hydrologische Systeme die Eigenschaft haben Niederschlag und Schmelzwasser bei der Abflussbildung zu dämpfen und damit zu verzögern ist es möglich Abflussvorhersagen zu machen ohne Niederschlags- und Temperaturprognosen zu verwenden. Diese Gegebenheit spielt eine wichtige Rolle in der heutigen Vorhersagepraxis. Dabei wird der Vorhersagetermin für kleinere Flussgebiete bestimmt von die natürliche Reaktionsdauer während in grösseren Flussgebieten das Verhalten von Abflusswellen im Flussbett von zusätzlicher Bedeutung ist für den Vorhersagetermin.

Für kleinere alpine Flussgebiete ist die Reaktionsdauer im allgemeinen klein (höchstens einige Tage), sodass man für eine längere Frist auf Grund dieser konventionellen Methode, angewiesen ist auf für diesen Zweck unzuverlässige Niederschlags- und Temperaturprognosen.

Diese Dissertation umfasst vier Kapitel. In Kapitel I wird das hydrologische Verhalten analysiert und beschrieben nach pluviale, nivale und glaziale Regimekomponenten und ihrer Bedeutung für das gesamte Abflussregime, abhängig von der Jahreszeit (Fig. 1.8, S. 1.10 und Fig. 1.14, S. 1.16). Durch einen extrem hohen Basisabfluss ausser den Wintermonaten sichern das nivale und das glaziale Subsystem diese Gebiete vor Niedrigwasser während langer Perioden ohne Niederschlag (Fig. 1.15, S. 1.17).

Eine Analyse von dem Zusammenhang zwischen Abflussverhalten und Wetterlagen erfordert eine objektive Klassifikation von Wetterlagen. In Kapitel II wird auf das Begriff Wetterlagenklassifikation eingegangen und wird eine Übersicht gegeben von bestehenden Klassifikationssystemen. Weil Niederschlag und Temperatur die wichtigsten äusserlichen Faktoren für die Bildung von Abflüssen sind, wurde bei der Wahl des zu verwendenden Klassifikationssystems der Zusammenhang zwischen diesen meteorologischen Parametern und den verschiedenen Wetterlagen als Kriterium verwendet. Auf diesen Grund liefert das Schüepp'sche (1968) System die besten Erfolge.

Das Schüepp'sche Klassifikationssystem von Wetter- und Witterungslagen wurde für diese Untersuchung als Basis verwendet. Mit diesem System (Schema 2.2, S. 2.14) wurden auf Grund der in das Flussgebiet der Ahr und ihrer direkten Umgebung beobachteten Niederschläge und Temperaturen insgesamt 8 hydrologisch-relevante Klassen von Wetterlagen definiert, basiert auf:

a) eine Einteilung nach Luftmassen in Zusammenhang mit Temperaturabweichungen vom Normalwert,
b) eine Einteilung nach Zyklonalität (Schema 2.5, S. 2.36 und 2.37).

Die Zusammenhänge zwischen obenerwähnten Klassen von Wetterlagen und Abfluss wird beschrieben in Kapitel III, auf Grund einer Zahl von statistischen Parametern. Die Unterschiede im Abflusscharakter bei den verschiedenen Klassen kommen deutlich zur Geltung in einer Vergleichung der Variabilität der Abflüsse (Fig. 3.4, S. 3.7) und in einer Vergleichung der mittleren täglichen Abflussänderungen (Fig. 3.5, S. 3.8). Antizyklonale N/E-Zirkulation zeigt fast das ganze Jahr hindurch negative Werte (der Abfluss fällt also durchschnittlich) und zyklonale SE/NW-Zirkulation positive Werte (der Abfluss steigt also durchschnittlich), wobei aber die Unterschiede der mittleren Abflüsse verhältnismässig gering sind (Fig. 3.3, S. 3.5). Dies weist darauf hin dass der Abfluss in hohem Masse zusammenhängt mit dem Charakter der vorhergehenden Wetterlagen, was auch deutlich hervorgeht aus einer Varianz-Analyse von Abflüssen während der einzelnen Klassen. Der *Charakter* der Wetterlage bestimmt also den *Charakter* des Abflusses nach Variabilität, Abnahme oder Zunahme des Abflusses. Das *Niveau* des Abflusses aber wird in hohem Masse bestimmt von dem *Niveau* der Ausgangsbedingungen und Autokorrelation. Die Ausgangsbedingungen werden hauptsächlich bestimmt von der Ausdehnung und den fysischen Eigenschaften des nivo-glazialen Subsystems. Die Autokorrelation hängt zusammen mit den charakteristischen Zeiten der während der vergangenen Wetterlagen aktiven pluvialen, nivalen und glazialen Subsystemen.

Statistische Beziehungen wurden bestimmt zwischen Klassen von Wetterlagen und

1) die Erwartungswerte der Temperaturabweichung vom Normalwert,
2) die Erwartungswerte der Niederschläge.

Auf diesen Grund wurde ein auf Wetterlagen basiertes Modell entwickelt für Vorhersagen des mittleren Abflusses über mittelfristige Perioden (10 Tage). Dieses Modell wird beschrieben in Kapitel IV. Das Modell ist basiert auf eine Mehrfachregression zwischen dem abhängigen Variable (Abfluss) und einer Gruppe von abhängigen Variablen. Diese letzten wurden eingeteilt in AUSGANGS-VARIABLEN, verbunden mit Gebietsverhältnissen welche bekannt sind im Moment der Vorhersage und KÜNFTIGEN VARIABLEN welche den Wetterkarten entnommen werden können. Die künftigen variablen sind weiter untereingeteilt in:

a) Variablen welche bestimmt werden auf Grund von prognostischen Wetterkarten durch eine Übersetzung nach Wettertypen (ÜBERSETZUNGSMETHODE),
b) Variablen welche direkt den Wetterkarten entnommen werden können (DIREKTE METHODE).

Die Regressionanalysen wurden einzeln durchgeführt für die Monate Mai bis September. Die übrigen Monate wurden nicht in die Analyse bezogen wegen des stabilen Charakters des Abflusses in dieser Periode.

Da es sich hier um die Anwendbarkeit von prognostischen Wetterkarten für Abflussvorhersagen handelt, wurde eine deutliche Trennung gemacht zwischen:

a) die Vorhersage von Wetterkarten (Fachbereich der Meteorologie)
b) die Verwendung von prognostischen Wetterkarten für Abflussvorhersage auf mittelfristige Termin.

Es wurde daher nur von richtigen Wetterkarten ausgegangen.

Das Modell wurde, anschliessend an die von dem ECMWF vorhergesagten 10-tägigen Prognosekarten gebraucht für die Vorhersage von:

1) den mittleren Abfluss über 10 Tage,
2) den höchsten Tagesabfluss während der nächsten 10 Tage,
3) den niedrigsten Tagesabfluss während der nächsten 10 Tage.

Das Modell wurde getestet auf Grund der 22-jährige Periode (1953-1974). Das kombinierte Auftreten von künftigen Variablen, bestimmt nach der Übersetzungsmethode, sowohl als nach der direkten Methode, lieferte die besten Erfolge. Dies wird die KOMBINIERTE METHODE genannt. Namentlich die Vorhersage des mittleren Abflusses über 10 Tage lieferte befriedigende Erfolge, mit Korrelationskoeffizienten zwischen tatsächlichen und vorhergesagten Abflüssen von 0.86 (August) bis 0.89 (Juni) und eine erklärte Varianz der abhängigen Variable von 74% bis 80%.

Die Korrelationskoeffiziente, gefunden für die Vorhersage des höchsten und des niedrigsten Tagesabflusses während der nächsten 10 Tagen, schwanken zwischen 0.73 (Juni) und 0.78 (Mai) für die höchsten und zwischen 0.54 (Juni) und 0.89 (September) für die niedrigsten Tagesabflüsse.

Die in die Regressionsgleichungen auftretenden Variablen zeigen ganz deutlich die relative Bedeutung der pluvialen, nivalen und glazialen Subsysteme für das gesamte Abflussregimes abhängig von der Jahreszeit.

S A M E N V A T T I N G

In dit proefschrift wordt de samenhang beschreven tussen het afvoergedrag van een alpien stroomgebied en het totale weerbeeld, zoals dat uit de weerkaart kan worden bepaald door middel van een vertaling naar weertypen. Op grond hiervan kon een op weertypen gebaseerd model voor de voorspelling van afvoeren op middellange termijn worden ontwikkeld. Hiermee wordt een nieuwe methode geïntroduceerd voor voorspelling van rivierafvoeren op middellange termijn, ter opvulling van de leemte tussen methoden voor voorspelling op korte termijn (tot enkele dagen) en op lange termijn (enkele weken tot maanden). Hiermee wordt tevens de aanzet gegeven tot een nieuwe vorm van integratie van de beide disciplines der *hydrologie* en *meteorologie*, leidend tot een op weertypen gebaseerde methodiek voor afvoervoorspelling. Als richtlijn voor de middellange termijn werden de 10-daagse perioden aangehouden, waarvoor het "European Centre for Medium Range Weather Forecast (ECMWF)", in Reading, Engeland, 1000 mb- en 500 mb-kaarten voorspelt van West-Europa.

De methode werd toegepast op het bovenstroomse deel van het alpine stroomgebied van de Ahr (fig. 1.1, pg. 1.1). Dit stroomgebied ligt juist ten zuiden van de centrale alpenkam in de Zillertaler Alpen. Het heeft een oppervlakte van 148 km^2 en de hoogte varieert tussen 1035 m en 3499 m boven zeeniveau (fig. 1.2, pg. 1.3). Voor het onderzoek werd gebruik gemaakt van hydrologische en meteorologische gegevens over de 23-jarige periode 1953-1975.

Alpine stroomgebieden zijn door de tijdelijke opslag van water in de vorm van sneeuw en ijs en de daarmee samenhangende niveo-glaciale regimecomponenten in de rivierafvoer van grote betekenis voor de energieopwekking en vormen door de grote voorraadvorming potentiële waterwingebieden.

Voor een optimaal waterhuishoudkundig beheer van deze stroomgebieden (afvoerbeheersing, regulatie van stuwmeren etc.) zijn afvoervoorspellingen op middellange termijn essentieel.

Hydrologische systemen hebben de eigenschap neerslag en smeltwater vertraagd tot afvoer te laten komen, waardoor het mogelijk is afvoervoorspellingen te doen, zonder daarbij gebruik te maken van neerslag- en temperatuurvoorspellingen. Het gebruik maken van deze vertraging speelt een belangrijke rol in de huidige praktijk van afvoervoorspelling. Hierbij wordt de termijn van voorspelling voor de kleinere stroomgebieden bepaald door het natuurlijke spectrum van vertragingstijden, terwijl bij de grotere stroomgebieden het gedrag van afvoergolven in het rivierensysteem mede bepalend is voor de voorspellingstermijn.

Voor kleinere alpine stroomgebieden blijft het vertragingsspectrum in het algemeen beperkt tot enkele dagen. Voor voorspellingen die deze termijn overschrijden is men dus bij gebruik van deze conventionele methoden aangewezen op voor dit doel onvoldoende betrouwbare neerslag- en temperatuurvoorspellingen.

Het proefschrift bevat vier hoofdstukken. In hoofdstuk I wordt het hydrologisch gedrag geanalyseerd en beschreven in termen van pluviale-, nivale- en glaciale regimecomponenten en hun betekenis binnen het totale afvoerregime in afhankelijkheid van de tijd van het jaar (fig. 1.8, pg. 1.10 en fig. 1.14, pg. 1.16). Het nivale subsysteem en het glaciale subsysteem zijn samen verantwoordelijk voor een extreem hoge basisafvoer buiten de wintermaanden, waardoor deze gebieden gevrijwaard zijn van lage afvoeren gedurende lange perioden zonder neerslag (fig. 1.15, pg. 1.17).

Bestudering van de samenhang tussen afvoergedrag en weertypen vereist een objectieve classificatie van weertypen. In hoofdstuk II wordt ingegaan op het begrip weertypen-classificatie en wordt een overzicht gegeven van bestaande classificatiesystemen. Aangezien neerslag en temperatuur de belangrijkste invoerbepalende factoren zijn van het afvoergenererende hydrologische systeem, werd bij de keuze van het te gebruiken classificatiesysteem de samenhang tussen deze meteorologische parameters en de onderscheiden weertypen als criterium gebruikt. Op grond hiervan levert het classificatiesysteem van Schüepp (1968) de beste resultaten op.

Het classificatiesysteem van weertypen van Schüepp werd gebruikt als basis voor het onderzoek. Gebruik makend van dit systeem (schema 2.2, pg. 2.14) werden op grond van in het stroomgebied van de Ahr en haar directe omgeving waargenomen neerslagen en temperaturen in totaal 8 hydrologisch-relevante klassen van weertypen gedefinieerd, gebaseerd op:

a) een indeling naar luchtsoorten in combinatie met temperatuurafwijkingen t.o.v. normaal,
b) een indeling naar cyclonaliteit (schema 2.5, pg. 2.36 en 2.37).

De samenhang tussen bovengenoemde klassen van weertypen en de afvoer wordt behandeld in hoofdstuk III op basis van een aantal statistische grootheden. Het verschil in karakter van de afvoer tijdens de verschillende klassen van weertypen komt duidelijk naar voren bij een vergelijking van de variabiliteit van de afvoer (fig. 3.4, pg. 3.7) en bij een vergelijking van de gemiddelde dagelijkse verandering van de afvoer (fig. 3.5, pg. 3.8). Anticyclonale N/E-circulatie vertoont bijna het gehele jaar gemiddeld een neiging tot afvoerdaling terwijl cyclonale SE/NW-circulatie gemiddeld een neiging tot afvoerstijging vertoont. Het gemiddelde verloop van de afvoer over ruim twintig jaar vertoont desondanks betrekkelijk geringe verschillen (fig. 3.3, pg. 3.5). Dit wijst erop dat de afvoer in sterke mate samenhangt met het karakter van voorafgaande weertypen, hetgeen tevens blijkt uit een variantie-analyse van de afvoeren binnen de afzonderlijke klassen. Het *karakter* van het weertype bepaalt dus het *karakter* van de afvoer in termen van variabiliteit, daling of stijging. Het *niveau* van de afvoer wordt echter voor een belangrijk deel bepaald door het *niveau* van de antecedente condities en autocorrelatie. De antecedente condities worden voornamelijk bepaald door omvang en fysische eigenschappen van het niveo-glaciale subsysteem. De autocorrelatie hangt samen met de leegloopkarakteristieken van de tijdens de voorafgaande weertypen werkzame pluviale, nivale en glaciale subsystemen.

Statistische verbanden werden aangetoond tussen de klassen van weertypen en

1) de verwachtingswaarde van de temperatuurafwijking t.o.v. normaal,
2) de verwachtingswaarde van de neerslag.

Op basis daarvan werd een op weertypen gebaseerd model ontwikkeld voor de voorspelling van de gemiddelde afvoer op middellange termijn (10 dagen). Dit model staat beschreven in hoofdstuk IV. Het model is gebaseerd op een meervoudige regressie tussen de afhankelijke variabele (afvoer) en een groep onafhankelijke variabelen. Deze laatste werden gesplitst in UITGANGSVARIABELEN, samenhangend met stroomgebiedsomstandigheden die reeds bekend zijn op het moment van voorspelling en TOEKOMSTIGE VARIABELEN die kunnen worden ontleend aan voorspelde weerkaarten. De toekomstige variabelen zijn verder onderverdeeld in:

a) variabelen die worden bepaald op basis van de voorspelde weerkaart door middel van een vertaling naar weertypen (VERTAAL METHODE),
b) variabelen die direkt aan de weerkaart worden ontleend (DIREKTE METHODE).

De regressie-analyses werden afzonderlijk per maand uitgevoerd voor de maanden mei t/m september. De andere maanden werden niet in de analyse betrokken vanwege het stabiele karakter van de afvoer in die periode.

Aangezien het hier primair gaat om het toetsen van de bruikbaarheid van voorspellende weerkaarten bij de afvoervoorspelling, werd er een duidelijke scheiding gemaakt tussen:

a) het voorspellen van weerkaarten (het terrein van de meteorologie),
b) het gebruik maken van voorspellende weerkaarten voor afvoervoorspelling op middellange termijn.

Bij het testen van het model werd daarom uitgegaan van correcte, achteraf samengestelde weerkaarten.

Het model werd, in aansluiting op de tiendaagse door het ECMWF voorspelde weerkaart, gebruikt voor de voorspelling van:

1) de gemiddelde afvoer over tien dagen,
2) de hoogste dagafvoer gedurende de komende tien dagen,
3) de laagste dagafvoer gedurende de komende tien dagen.

Het model werd getest op basis van de 22-jarige periode (1953-1974). Het gecombineerde gebruik van toekomstige variabelen, bepaald volgens de vertaalmethode zowel als volgens de direkte methode, leidde tot de beste resultaten. In dit proefschrift wordt dit de GECOMBINEERDE METHODE genoemd. Met name de voorspelling van de tiendaagse gemiddelde afvoer leverde bevredigende resultaten op, met correlatie-coefficienten tussen waargenomen en voorspelde afvoer variërend tussen 0.86 voor de maand augustus en 0.89 voor de maand juni en met een verklaarde variantie van de afhankelijke variabele respectievelijk tussen 74% en 80%.

De correlatie-coefficienten, gevonden voor de voorspelling van de hoogste en de laagste dagafvoer gedurende de komende 10 dagen, variëren tussen 0.73 (juni) en 0.78 (mei) voor de hoogste en tussen 0.54 (juni) en 0.89 (september) voor de laagste dagafvoer.

De in de regressievergelijkingen optredende variabelen geven een duidelijk beeld van het relatieve belang van de pluviale, nivale en glaciale subsystemen voor het totale afvoerregime, in afhankelijkheid van de tijd van het jaar.

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APPENDIX A

STATISTICAL METHODS

1 Linear Regression Analysis

1.1 Bivariate Linear Regression

1.2 Multiple Linear Regression

2 Linear Correlation Analysis

2.1 Bivariate Linear Correlation

2.2 Multiple Linear Correlation

2.3 Partial Correlation Analysis

3 Comparison of Populations

3.1 Analysis of Variance

3.2 Multinomial Analysis

4 Factor Analysis

STATISTICAL METHODS

Statistical methods used in this thesis are summarized as follows. For further information on the methods used and their theoretical details, the reader is referred to the specific literature concerned.

. Linear Regression Analysis

1.1 Bivariate Linear Regression

Assume a sample of n observations x_i, y_i (i=1,...,n), drawn from a two dimensional population of the variables X and Y. The linear association between the variables can be expressed by the coefficient of correlation between X and Y. The form of this linear association is expressed by the regression of Y with respect to X, where X is assumed to be the independent variable and Y the dependent variable.

The most common method of finding the linear equation of best fit to observed data is the Gaussian principle of least squares. According to this method a line is fitted to the data points in such a manner that the sum of squares of the deviations of the individual points from that line is minimized, or

$$\sum (y_i - Y_i')^2 = \text{minimum} \tag{1}$$

where Y_i' = i^{th} estimated value of the dependent variable
y_i = i^{th} observed value of the dependent variable

The equation of the bivariate regression is

$$Y' = a + bX \tag{2}$$

where Y' = estimated dependent variable
X : independent variable
a : regression constant *(or intercept)*; $a = \overline{y} - b\overline{x}$, with $\overline{y} = \frac{1}{n}\sum y_i$ and $\overline{x} = \frac{1}{n}\sum x_i$
b : regression coefficient

The regression coefficient has the form

$$b = \frac{s_{xy}}{s_x^2} \tag{3}$$

where $s_{xy} = \frac{1}{n-1} \sum(x_i - \bar{x})(y_i - \bar{y})$ *(covariance of the sample)* (4)

$$s_x^2 = \frac{1}{n-1} \sum(x_i - \bar{x})^2 \quad \textit{(variance of x)} \tag{5}$$

The standard deviation of the x-variable is s_x. The standard deviation divided by the mean ($\bar{x}$) is the coefficient of variation, or

$$C_{v_{(x)}} = \frac{s_x}{\bar{x}} \tag{6}$$

Standard Error of Estimate

The residuals of the straight-line regression are $y_i - Y_i'$. The sum of squares of the residuals equals

$$\sum(y_i - Y_i')^2 = \sum(y_i - \bar{y})^2 - \sum(Y_i' - \bar{y})^2 \tag{7}$$

and the ratio

$$s_*^2 = \frac{\sum(y_i - Y_i')^2}{f_2} \tag{8}$$

is an estimate of the variance of the population of residuals, also denoted the standard error of estimate (S.E.E.), where $f_2 = n-2$ (degrees of freedom).

Significance of Regression Coefficient

If the regression coefficient β equals zero and if y is normally distributed for any fixed x, then the ratio

$$F = \frac{\frac{1}{f_1} \sum(Y_i' - \bar{y})^2}{\frac{1}{f_2} \sum(y_i - Y_i')^2} \tag{9}$$

represents a sample of a population which is F-distributed, with $f_1 = 1$ and $f_2 = n-2$ degrees of freedom. For $F > F_p$ the hypothesis ($\beta=0$) is rejected, which means that the coefficient of regression is significantly different from zero, with a probability of p.

Equation 9 can also be written as

$$F = \frac{b^2}{s_*^2} \cdot \sum(x_i - \bar{x})^2 \tag{10}$$

For $f_1 = 1$, F can be replaced by t^2 so that the t-test can be applied, where

$$t = \frac{|b|}{s_*} \cdot \sqrt{\sum(x_i - \bar{x})^2} \tag{11}$$

For a certain probability p and $f_2 = (n-2)$ degrees of freedom, the hypothesis (β=0) is rejected if the condition

$$\frac{|b|}{s_*} \cdot \sqrt{\sum(x_i - \bar{x})^2} \geqq t(p,f_2) \tag{12}$$

is satisfied.

1.2 Multiple Linear Regression

The multiple linear regression model assumes the prediction of the variable Y by means of a linear function of the variables X_j (j=1,...,m),

$$Y' = a + b_1X_1 + b_2X_2 + . . + b_mX_m \tag{13}$$

where the coefficients b_j are unknown and should be estimated from observed values of X_j.

Here also, the method of least squares is applied to find the coefficients b_j such that the sum of squares of the deviations of the individual points in an m-dimensional space from the linear function is minimized.

If the sample of n observations of the dependent variable Y and the independent variables X_j (j= 1,...,m) is taken, then the constant a is computed according to

$$a = \bar{y} - b_1\bar{x}_1 - b_2\bar{x}_2 - . . . - b_m\bar{x}_m \tag{14}$$

Substitution of eq. 14 into eq. 13 gives

$$Y' = y + b_1(x_1 - \bar{x}_1) + . . + b_m(x_m - \bar{x}_m) \tag{15}$$

For m independent variables the regression coefficients b_j $(j=1,\ldots,m)$ are computed from

$$b_j = c_{j1}\, s_{(x_1y)} + c_{j2}\, s_{(x_2y)} + \ldots + c_{jm}\, s_{(x_my)} \tag{16}$$

where $c_{jk} = c_{kj}$ are the Gaussian products, and

$$s_{(x_jy)} = \sum_{i=1}^{n} (x_{j1} - \bar{x}_j)(y_i - \bar{y}) \tag{17}$$

The standard error of estimate is

$$s_* = \sqrt{\frac{\sum(y_i - Y_i')^2}{n-m-1}} \tag{18}$$

where n = number of samples

m = number of independent variables

Significance of Regression Coefficients

In this case, the hypothesis $(\beta_j=0)$ can also be tested using the t-distribution. The t-value of the sample is computed from

$$t = \frac{b_j}{s_* \sqrt{c_{jj}}} \tag{19}$$

where $$s_* = \sqrt{\frac{\sum(y_j - Y_j')^2}{f}} \tag{20}$$

f = degrees of freedom (f = n-m-1)

n = number of samples

m = number of independent variables

c_{jj} = Gaussian products

The hypothesis $(\beta_j=0)$ is rejected if the condition

$$\frac{b_j}{s_* \sqrt{c_{jj}}} \geq t(p,f)$$

is satisfied.

2 Linear Correlation Analysis

2.1 Bivariate Linear Correlation

The ratio of the variance of the dependent variable, estimated from the linear regression equation, to the variance of the observed dependent variable is a measure for the association between both data series. It is called the coefficient of determination D, defined as

$$D = \frac{\frac{1}{n-1} \sum(Y_i^{'} - \bar{y})^2}{\frac{1}{n-1} \sum(y_i - \bar{y})^2} \tag{21}$$

It is a measure of the degree to which the variance or square of the standard deviation, s_x^2 and s_y^2, is explained or accounted for by the linear regression. Equation 21 can also be written as

$$D = \frac{s_{xy}^2}{s_x^2 \cdot s_y^2} \tag{22}$$

The coefficient of correlation r is the square root of D

$$r = \sqrt{D} = \frac{s_{xy}}{s_x \cdot s_y} \tag{23}$$

and varies between -1 and +1.

Significance of Correlation Coefficient

The significance of the correlation coefficient is tested by employing the F-test. Equation 9 can be written as

$$F = \frac{(n-2)\ D}{(1-D)} \tag{24}$$

which is tested with $f_1 = 1$ and $f_2 = n-2$ degrees of freedom.

2.2 Multiple Linear Correlation

The coefficient of determination of a multiple linear regression equation follows from eq. 21, where Y_i is the estimated dependent variable using the multi-linear regression equation. The significance test of the multiple linear correlation coefficient r ($r = \sqrt{D}$), is also performed using the F-test, where

$$F = \frac{(n-m)\ D}{(m-1)(1-D)} \tag{25}$$

with f_1, f_2 degrees of freedom, where f_1 equals the number of independent variables (m) and f_2 equals (n-m-1).

2.3 *Partial Correlation Analysis*

If the variation of the dependent variable Y is explained by more than one independent variable, it may be useful to compute partial correlation coefficients in order to separate the influences of the individual independent variables on the variation of the dependent variable. The partial correlation coefficient is a measure of the association between the dependent variable Y and any of the given dependent variables X_i, while the influence of the other dependent variables is eliminated. The partial correlation coefficient r_{Y,X_i} is computed according to

$$r_{Y,X_i} = \frac{(1 - r^2_{-X_i}) - (1 - r^2)}{1 - r^2_{-X_i}} \tag{26}$$

where r = multiple linear correlation coefficient between Y and X_j ($j=1,\ldots,m$)

r_{-X_i} = multiple linear correlation coefficient between Y and all X_j, except X_i

3 Comparison of Populations

3.1 *Analysis of Variance*

A comparison of several sets of observations, in order to conclude whether or not the sets are coming from the same population, may be carried out by means of analysis of variance. The analysis is based on the F-test (see for ex. Hald, 1965).

Consider k samples of n_k observations, drawn randomly from a normally distributed population with a mean ξ and a variance σ^2. A comparison of the k samples then results in k sample means and k sample variances.

If the i^{th} sample has n_i observations, then each observation is denoted $X_{i,j}$ $(i=1,\ldots,k;\ j=1,\ldots,n_i)$, and the sum of all observations N, where

$$N = \sum_{i=1}^{k} n_i \tag{27}$$

The mean of all $X_{i,j}$ is denoted $\bar{x}$ and the mean of the i^{th} sample is denoted $\bar{x}_i$. The total estimated variance s^2 is split into the variation s_E^2 between the samples *(external variance)* and in the variation s_I^2 within the samples *(internal variance)*, according to

$$(N-1)\ s^2 = (k-1)\ s_E^2 + (N-k)\ s_I^2 \tag{28}$$

where

$$(N-1)\ s^2 = \sum_{i=1}^{k} \sum_{j=1}^{n_i} (X_{i,j} - \bar{x})^2$$

$$(k-1)\ s_E^2 = \sum_{i=1}^{k} n_i\ (\bar{x}_i - \bar{x})^2$$

$$(N-k)\ s_I^2 = \sum_{i=1}^{k} \sum_{j=1}^{n_i} (X_{i,j} - \bar{x}_i)^2$$

The hypothesis that the different samples come from the same normally distributed population is tested at a significance level p, using Fischer's F-test, where

$$F = \frac{s_E^2}{s_I^2} \tag{29}$$

with $f_1 = (k-1)$ and $f_2 = (N-k)$ degrees of freedom. The hypothesis is rejected if

$$\frac{s_E^2}{s_I^2} \geqq F^t(p, f_1, f_2) \tag{30}$$

3.2 Multinomial Analysis

Consider a sample of n observations drawn from a multinomial distribution of k classes. The probability of occurrence of each class is denoted π_i, with

$$\sum_{i=1}^{k} \pi_i = 1 \tag{31}$$

Let $x_1, \ldots, x_k$ be the observed frequencies in the sample of n observations. To test the hypothesis that the sample is drawn randomly from the multinomial distribution, the following criterion is used

$$\chi^2 = \sum_{i=1}^{k} \frac{(x_i - n \quad _i)^2}{n\,\pi_i} = \sum \frac{(\text{Observed} - \text{Expected})^2}{\text{Expected}} \tag{32}$$

or $$\chi^2 = \sum \frac{O^2}{E} - \sum O$$

where $n = \sum_{i=1}^{k} x_i$, and which is approximately distributed as χ^2 with $f_1 = k-1$ degrees of freedom, if all $n\pi_i > 5$ (see e.g., Rao, 1965). At a significance level p, the hypothesis is rejected if

$$\left(\sum \frac{O^2}{E} - \sum O\right) > \chi^2(p, f_1) \tag{33}$$

4 Factor Analysis

The objective of factor analysis is to represent a large number of variables by a reduced number of hypothetical entities or factors in order to draw conclusions about mutual relationships between the variables and about the structure of the whole sample.

Basic Equations

All observations of the variables are represented by a matrix $X = (x_{i,j})$, where $i=1,2,\ldots,m$ are the variables and $j=1,2,\ldots,n$ are the observations.

The basic set of equations for factor analysis is the correlation matrix R

$$R = \frac{1}{n-1} X \cdot X' \tag{34}$$

where X' is the transposed matrix of X. The basic model of factor analysis is represented by the equation

$$X = A \cdot P \tag{35}$$

where A is the m·r matrix of factor loadings and P is the r·n matrix of factor values. The factor loadings represent the association between the factor concerned and the variables.

Substitution of eq. 35 in eq. 34 leads to

$$R = \frac{1}{n-1} X \cdot X' = A \frac{1}{n-1} P \cdot P' \cdot A \tag{36}$$

or

$$R = A \cdot C \cdot A' \tag{37}$$

where $C = \frac{1}{n-1} P \cdot P'$, the correlation matrix between the factors. If the factors are uncorrelated, i.e., C = indentity matrix (I), it follows that

$$R = A \cdot A' \tag{38}$$

Computation of Factor Loadings

Equation 38 is solved under the precondition that the sum of squares of factor loadings of the first factor explains a maximum of the total variance and that of the next factor explains a maximum of the remaining variance. This is expressed by

$$\lambda_j = \sum_{i=1}^{m} a_{i,j} = \text{maximum} \tag{39}$$

A general form for the solution of eq. 39 is

$$(R - \lambda_j \cdot I)\ \alpha_j = 0 \tag{40}$$

where λ_j is the eigenvalue of the j^{th} factor and α_j is the corresponding eigenvector of R.

Substitution of λ_1 in eq. 39 leads to the vector $(\alpha_{1,1}, \alpha_{2,2}, \ldots, \alpha_{m,1})$ for which the summation

$$\sum_{i=1}^{m} (\alpha_{i,1})^2 \quad \text{is a maximum}$$

The values of the loadings $a_{i,j}$ are found from the equation

$$a_{i,j} = \alpha_{i,j} \frac{\lambda_j}{\sqrt{(\alpha_{1,j})^2 + (\alpha_{2,j})^2 + \ldots + (\alpha_{m,j})^2}} \tag{41}$$

and represent the association (to be interpreted as a correlation coefficient) of the variable i with the factor F_j, where i=1,2,...,m and j=1,2,..,r. The sum of squares of the loadings of the i^{th} variable in each factor (j=1,2,...,r) is called the communality, given by

$$h_i^2 = \sum_{j=1}^{r} (a_{i,j})^2 \tag{42}$$

APPENDIX B

MATHEMATICAL MODEL FOR HYDROGRAPH ANALYSIS

Hydrograph analysis from snow covered areas and areas containing glaciers becomes even more complex when runoff from precipitation forms part of the total runoff. Such hydrographs usually cannot be analysed by simple graphical plotting techniques since snow melt runoff is hardly ever in complete recession flow.

To gain insight into the complex character of such hydrographs, they should be split into appropriate terms corresponding to the runoff contribution of the different sub-systems distinguished in chapter I, each having its own characteristic time.

Assuming that the storages of the nivo-glacial system and the pluvial system both act according to the *"linear reservoir concept"*, each having its own terms of input and runoff output, a method is used to separate the complex hydrograph in the appropriate parts and to find optimal values of the storage characteristics in terms of characteristic times.

The Nivo-Glacial Runoff Component

The nivo-glacial system is simulated by a linear storage which, when sufficient melt occurs, is predominantly filled during the day-time and emptied during the night-time. As a result of the storage and transportation through the snow- and glacier bodies - and subsequently through underlying soil-covers or bare rock - the runoff process is accompanied by a certain retention-delay. Only part of the daily melt water will reach the outlet during the corresponding day, with the remainder discharging during the following days as recession flow with a gradually decreasing rate dependent on the characteristics of the systems. As a reflection of antecedent melt occurrences these flows in recession will together form a smoothly oscillating type of base flow as shown in fig. B-1. The melt which occurred on the third day equals the shaded area.

The Pluvial Runoff Component

For the pluvial system it is also assumed that only part of the effective daily rainfall will leave the catchment that very day, while the remainder is temporarily stored to be released as delayed runoff, simulated by another linear storage.

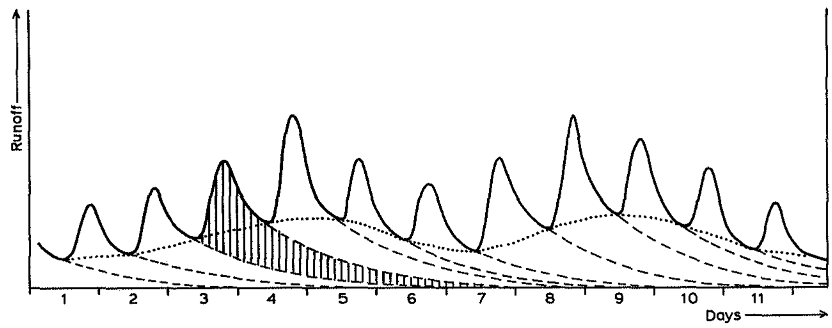

Fig. B-1 Interpretation of a melt-water hydrograph. The shaded area represents the total runoff corresponding to the melt generated during the third day. The base flow is indicated by the dotted line

Basic System Equations

For a linear storage, the storage $S(t)$ at time t is proportional to the outflow $q(t)$ according to

$$S(t) = k \cdot q(t) \tag{1}$$

where k is the storage coefficient *(or characteristic time)* with the dimension of time. If no inflow occurs the equation of continuity becomes

$$\frac{dS(t)}{dt} = - q(t) \tag{2}$$

After differentiation of eq.1 in combination with eq.2, it follows that

$$k \frac{dq(t)}{dt} = - q(t) \tag{3}$$

and using the condition that the outflow equals q(0) at t=0, equation 3 is solved as

$$q(t) = q(0) \cdot e^{-\frac{1}{k} t} \tag{4}$$

which, for two consecutive moments, Δt apart, can be written as

$$q(t) = q(t - \Delta t) \cdot e^{-\frac{1}{k} \Delta t} \tag{5}$$

Now, if we assume an input $I(t)$ at time t into the storage, this volume equals the summation of successive discharges $q'(t)$ (for t=1, $t+\Delta t$, $t+ 2\Delta t$, ., ∞) according to the recurrence given by eq.5

$$I(t) = q'(t) \sum_{n=0}^{\infty} \left\{ e^{-\frac{1}{k}\Delta t} \right\}^{n} \tag{6}$$

which as a summation of geometric series can be written as

$$I(t) = q'(t) \frac{1 - \left\{ e^{-\frac{1}{k}\Delta t} \right\}^{\infty}}{1 - e^{-\frac{1}{k}\Delta t}} \tag{7}$$

With $e^{-\frac{1}{k}\Delta t} < 1$ *(which is always true for* $k > 0$*)*, eq.7 becomes

$$I(t) = q'(t) \frac{1}{1 - e^{-\frac{1}{k}\Delta t}}$$

or

$$q'(t) = I(t)\cdot(1 - e^{-\frac{1}{k}\Delta t}) \tag{8}$$

Accounting for the runoff from the reservoir as a result of preceding inputs, the total outflow at time t is found from the summation of eq.5 and eq.8 giving

$$q(t) = q(t - \Delta t)\cdot e^{-\frac{1}{k}\Delta t} + I(t)\cdot(1 - e^{-\frac{1}{k}\Delta t}) \tag{9}$$

For each moment t the outflow $q(t)$ is computed from the outflow at $t-\Delta t$ and the input at time t.

Input from Snow- and Glacier Melt

To overcome the many difficulties which accompany computation of snowmelt and glacier melt (U.S. Army Corps of Eng., 1956; Garstka et al., 1958; Obled & Rosse, 1977) on the basis of physical considerations, arising from the wide variations both in time and in space of the melt governing factors, a snow-cover index I_s is introduced. This is defined as the generated amount of freely drainable melt per day and per degree of maximum daily temperature above 0 ^{o}C.

The basic equation of the melt system thus becomes

$$q_s(t) = q_s(t - \Delta t)\cdot e^{-\frac{1}{k_s}\Delta t} + I_s\cdot Tm(t)\cdot(1 - e^{-\frac{1}{k_s}\Delta t}) \tag{10}$$

where $q_s(t)$: melt component of runoff during the day t (mm)

$Tm(t)$: maximum temperature during the day t (^oC)

I_s snow-cover index (mm/day/^oC)

k_s characteristic time of the directly drainable fictitious linear storage of the melt system (days)

Δt 1 day

Input from Rainfall

Measured precipitation is used as input into the linear reservoir which simulates the pluvial system. In order to account for evapotranspiration losses and losses due to precipitation falling as snow, a reduction factor called R is introduced. The basic equation for the pluvial system thus becomes

$$q_r(t) = q_r(t - \Delta t)\cdot e^{-\frac{1}{k_r}\Delta t} + R \cdot P(t) \cdot (1 - e^{-\frac{1}{k_r}\Delta t}) \tag{11}$$

where $q_r(t)$: pluvial component of runoff during the day t (mm)

$P(t)$: precipitation during the day t (mm)

R : precipitation reduction factor, i.e., that part of the total precipitation that will either runoff directly or will be stored directly in fluid form to leave the catchment as delayed runoff

k_r : characteristic time of the directly drainable fictitious linear reservoir of the pluvial system (days)

Δt 1 day

Mathematical Formulation of the Problem

The problem of estimating the model parameters is solved by means of a (non-linear) least squares technique. The following parameters need to be optimized:

K_s, K_r, I_s and R

where $K_s = e^{-\frac{1}{k_s}\Delta t}$ and $K_r = e^{-\frac{1}{k_r}\Delta t}$.

From the observations of temperature and precipitation during N consecutive days we have the N+1 equations

$$q_s(t) + q_r(t) = Q(t) \qquad (t=0,1,\ldots,N) \tag{12}$$

where $Q(t)$ is the measured discharge.

The dependency of $\left(q_s(t) + q_r(t)\right)$ on the parameters K_s, K_r, I_s and R can be determined by means of the recurrence relations (10) and (11), for all intervals $t=1,2,\ldots,N$, except for $t=0$. In order to express the terms $q_s(t)$ and $q_r(t)$ in the parameters using the recurrence equations, the initial values $q_s(0)$ and $q_r(0)$, which are also unknown, have been added as new parameters to the original set.

The new set of 6 parameters is written in vector notation as

$$\vec{x} = \left(K_s,\ K_r,\ I_s,\ R,\ q_s(0),\ q_r(0)\right)^T \tag{13}$$

By means of the recurrence relations (10) and (11), $q_s(t)$ and $q_r(t)$ are determined for all $t=1,2,\ldots,N$ as functions of the parameter vector $\vec{x}$. In explicit form these are rather complicated but their values are computed in implicite form by the given recurrences at a given point $\vec{x}$. Hence we may write

$$q_s(t) = q_s(t)\ \overrightarrow{(x)}$$

and

$$q_r(t) = q_r(t)\ \overrightarrow{(x)}$$

We put $F(t)\ \overrightarrow{(x)} = q_s(t)\ \overrightarrow{(x)} + q_r(t)\ \overrightarrow{(x)}$, and define the (N+1)-vector $\vec{F}\ \overrightarrow{(x)}$ as

$$\vec{F}\ \overrightarrow{(x)} = \left(F(0)\ \overrightarrow{(x)},\ F(1)\ \overrightarrow{(x)},\ \ldots,\ F(N)\ \overrightarrow{(x)}\right)^T \tag{14}$$

which is a non-linear map from the 6-dimensional parameter space into the (N+1)-dimensional space of discharge values.

The next step is to solve the equation

$$\vec{F}\ \overrightarrow{(x)} = \vec{Q} \tag{15}$$

where $\vec{Q} = \left(Q(0),\ Q(1),\ \ ,\ Q(N)\right)^T$, with $Q(t)$, the measured discharge value.

Noise effects are eliminated as far as possible by choosing N+1 much larger than 6 and eq.15 is solved using a least squares technique, i.e., $\vec{x}$ is determined such that the sum of the squares of residuals is minimized according to

$$\sum_{t=0}^{N} \left[F(t)\ \vec{(x)} - Q(t) \right]^2 = \text{Minimum} \tag{16}$$

or

$$\left[\vec{F}\ \vec{(x)} - \vec{Q} \right]^2 = \text{Minimum} \tag{17}$$

Let $\vec{x}^{\,j}$ be a first approximation in the least squares solution $\vec{x}$ of $\vec{F}\ \vec{(x)} = \vec{Q}$, and let $\vec{h}^{\,j} = \vec{x} - \vec{x}^{\,j}$. Hence by ignoring second- and higher order terms

$$\vec{F}\ \vec{(x)} = \vec{F}\,(\vec{x}^{\,j} + \vec{h}^{\,j})$$

can be developed in a Taylor-series as

$$\vec{F}\,(\vec{x}^{\,j}) + A^j\,\vec{h}^{\,j} \cong \vec{F}\ \vec{(x)} \tag{18}$$

where A^j is the Jacobian matrix of $\vec{F}$ evaluated at $\vec{x}^{\,j}$, i.e.,

$$A(k,l)^{\,j} = \frac{\partial}{\partial x(l)}\ F(k)\ (\vec{x}^{\,j}) \tag{19}$$

Substitution of eq.18 into eq.17 leads to the minimization of

$$\left[\vec{F}\,(\vec{x}^{\,j}) + A^j\,\vec{h}^{\,j} - \vec{Q} \right]^2 \tag{20}$$

which is a linear least squares problem in the unknown vector $\vec{h}^{\,j}$. The normal equations are given by

$$(A^j)^T\ (A^j)\ \vec{h}^{\,j} = (A^j)^T\ (\vec{Q} - \vec{F}\,(\vec{x}^{\,j})) \tag{21}$$

so that

$$\vec{h}^{\,j} = \left[(A^j)^T\ A^j \right]^{-1} (A^j)^T\ (\vec{Q} - \vec{F}\,(\vec{x}^{\,j})) \tag{22}$$

The procedure is continued by setting $\vec{x}^{\,j+1} = \vec{x}^{\,j} + \vec{h}^{\,j}$ and is stopped as soon as the term

$$\left[\vec{F}(\vec{x}^{\,n-1}) - \vec{F}(\vec{x}^{\,n})\right]$$

becomes less than a prescribed tolerance. Then $\vec{x}^{\,n}$ is taken as an approximation of $\vec{x}$, i.e., the minimizing parameter vector for

$$\left[\vec{F}(\vec{x}) - \vec{Q}\right]^2 \tag{23}$$

The method is known as the Gauss method for over-determined systems (see for ex. Kowalik and Osborne, 1968). A very useful variant has been proposed by Marquardt (1963) in which $\vec{h}^{\,j}$ is determined according to

$$\vec{h}^{\,j} = \left[(A^j)^T A^j + \mu I\right]^{-1}\left(\vec{Q} - \vec{F}(\vec{x}^{\,j})\right) \tag{24}$$

μ (>0) is a parameter, which, when carefully chosen, leads to a significant improvement in the performance of the method (Kowalik and Osborne, 1968). This latter approximation of $\vec{h}^{\,j}$ has been applied in the current model.

Recursive Computation of the Jacobian Matrix

The above algorithm requires computation of the vector $\vec{F}(\vec{x}^{\,j})$ for the given $\vec{x}^{\,j}$ and computation of the matrix A^j, i.e., the Jacobian matrix of $\vec{F}$ at $\vec{x}^{\,j}$. Thus we must compute the partial derivatives of $q_s(t)$ and $q_r(t)$ with respect to the parameters K_s, K_r, ..., $q_r(0)$. Since the recursion for the terms $q_m(t)$ does not depend on K_n for $m \neq n$, (m = s,r; n = s,r) we have

$$\frac{\partial}{\partial K_n} q_m(t)\ \overrightarrow{(x)} = 0 \quad \text{for} \quad m \neq n$$

Similarly, ot follows that

$$\frac{\partial}{\partial I_s} q_r(t)\ \overrightarrow{(x)} = 0$$

$$\frac{\partial}{\partial R} q_s(t) \overrightarrow{(x)} = 0$$

and $$\frac{\partial}{\partial q_n(0)} q_m(t) \overrightarrow{(x)} = 0 \qquad \text{for} \quad n \neq m$$

Consequently, only the following partial derivatives have to be determined:

$$\frac{\partial}{\partial K_n} q_n(t) \overrightarrow{(x)} \qquad \text{for} \quad n = r,s$$

$$\frac{\partial}{\partial q_n(0)} q_n(t) \overrightarrow{(x)} \qquad \text{for} \quad n = r,s$$

$$\frac{\partial}{\partial I_s} q_s(t) \overrightarrow{(x)}$$

$$\frac{\partial}{\partial R} q_r(t) \overrightarrow{(x)}$$

APPENDIX C

LIST OF GERMAN, ITALIAN AND ENGLISH NAMES

GERMAN	ITALIAN	ENGLISH
Ahr	Aurina	Ahr
Ahrntal	Valle Aurina	Ahr valley
Antholz	Anterselva	
Brixen	Bressanone	
Bruneck	Brunico	
Bozen	Bolzano	
Dreiherrenspitze	Picco dei Tre Signori	
Eisack	Isarco	
Etsch	Adige	
Kasern	Casère	
Lappach	Lappago	
Mühlbach	Riomolino	
Mühlwald	Selva dei Molini	
Neves	Neves	
Niederrasen	Rasun di Sotto	
Ochsenlenke	Costa dei Bovi	
Prettau	Predöi	
Rain in Taufers	Riva di Tures	
Rauchkofel	Monte Fumo	
Rienz	Rienza	
Sand in Taufers	Campo Tures	
Steinhaus	Ca'di Pietra	
St.Jakob	S.Giacomo	
St.Johann	S.Giovanni	
St.Lorenzen	S.Lorenzo	
Südtirol	Alto Adige	Southern Tyrol
Zillertaler Alpen	Alpi Aurine	Zillertal Alps